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SAN JOAQUIN MASTER DRAIN. EFFECTS ON WATER QUALITY OF SAN FRANCISCO BAY AND DELTA. APPENDIX PART C. NUTRIENTS AND BIOLOGICAL RESPONSE

Richard C. Bain, Jr., et al

Federal Water Pollution Control Administration
San Francisco, California

August 1968

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SAN JOAQUIN MASTER DRAIN

CALIFORNIA

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APPENDIX
PART C
NUTRIENTS AND BIOLOGICAL RESPONSE

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SOUTHWEST REGION
AUGUST, 1968

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EFFECTS OF THE
SAN JOAQUIN MASTER DRAIN
ON WATER QUALITY OF THE
SAN FRANCISCO BAY AND DELTA

APPENDIX
PART C
NUTRIENTS AND BIOLOGICAL RESPONSE

by

CENTRAL PACIFIC BASINS
COMPREHENSIVE WATER POLLUTION CONTROL PROJECT

U. S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMINISTRATION
SOUTHWEST REGION
SAN FRANCISCO, CALIFORNIA

AUGUST 1968

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TABLE OF CONTENTS

Page

LIST OF TABLES.. iii

LIST OF FIGURES... iv

CHAPTERS

I. INTRODUCTION.. 1

PURPOSE.. 1

SCOPE OF THE INVESTIGATION.. 1

AUTHORITY.. 3

ACKNOWLEDGMENTS.. 3

II. SUMMARY OF FINDINGS AND CONCLUSIONS.. 5

FINDINGS.. 5

CONCLUSIONS.. 6

III. DESCRIPTION OF THE STUDY.. 8

DESCRIPTION OF STUDY AREA.. 8

SAN JOAQUIN MASTER DRAIN.. 9

IV. WATER QUALITY AND BIOLOGICAL RELATIONSHIPS.. 12

PRIMARY PRODUCTION AND NUTRIENTS.. 13

ALGAL POPULATIONS.. 19

TEMPERATURE.. 22

SUSPENDED SEDIMENTS AND LIGHT PENETRATION.. 23

LIMITING FACTORS.. 27

V. NITROGEN - ALGAE MODEL.. 31

VI. ALGAE - DISSOLVED OXYGEN MODEL.. 34

INTRODUCTION.. 34

PREDICTIONS.. 41

TABLE OF CONTENTS (Continued)

Page

VII. DISSOLVED OXYGEN AND THE FISHERY........................ 46
- INTRODUCTION.. 46
- DISSOLVED OXYGEN AND TOXICITY......................... 47
- TEMPERATURE AND OXYGEN REQUIREMENTS.................. 47
- DISSOLVED OXYGEN AND FISH PHYSIOLOGY................. 49
- FOOD WEB RELATIONSHIPS................................ 51
- DISSOLVED OXYGEN CRITERIA............................. 52

VIII. FISH POPULATIONS.. 57
- INTRODUCTION.. 57
- FISH DISTRIBUTIONS.................................... 57
- FISH POPULATION MODEL................................. 62

IX. FISHERY VALUE DETRIMENTS................................ 67
- INTRODUCTION.. 67
- STRIPED BASS.. 68
- KING SALMON... 70
- AMERICAN SHAD... 71

X. EFFECTS ON OTHER USES................................... 74
- SHORELINE RESIDENTIAL DEVELOPMENTS................... 74
- BOATING AND NAVIGATION................................ 75
- RECREATION AND AESTHETICS............................ 79
- WILDLIFE PROPAGATION AND SUSTENANCE.................. 81

XI. BIBLIOGRAPHY.. 82

LIST OF TABLES

Table	Title	Page
1	Summary of Nitrogen and Phosphorus Inputs - San Pablo Bay, Suisun Bay and the Delta	11
2	Elementary Composition - Marine Phytoplankton	14
3	Ratios Involving Chlorophyll	15
4	Suspended Solids Concentrations - San Francisco Bay Estuary	23
5	Sediments and Light Penetration - Projections	27
6	Range of Dissolved Oxygen Predictions - Tidal Mixing Model	44
7	Some Published Records of Dissolved Oxygen Concentrations Lethal to Fish Life	48
8	Estimated Fishery Damages From Low Dissolved Oxygen Concentrations (Warm Water Fishery - Stanislaus River)	55
9	Anadromous Fish - Distribution Pattern	62
10	Angler Success Ratios	67
11	Striped Bass Fishery Detriments	69
12	King Salmon Fishery Detriments (Sport and Commercial Losses)	72
13	King Salmon Fishery Detriments (Commercial Losses Only)	72
14	American Shad Fishery Detriments	73
15	Shoreside Residential Developments	76
16	Projected Boat Hull Maintenance Costs	78
17	Economic Benefits of Recreational Activities	79

LIST OF FIGURES

Figure No.	Title	Following Page
1	Study Area	8
2	Primary Study Area	9
3	San Joaquin Drainage Area and Alternate Discharge Sites	10
4	Components of Fishery Detriment Predictions	12
5	Mean Observed Total Nitrogen Concentration	16
6	Nitrate Nitrogen Variations	17
7	Mean Phytoplankton Productivity - San Francisco Bay, May-August 1964	20
8	Chlorophyll Variations - Antioch Bridge	20
9	Chlorophyll Variations, Grizzly and Honker Bays	20
10	Water Temperature Variations - San Francisco Bay Estuary	22
11	Chamber Studies - Western Delta	28
12	Chamber Studies - Carquinez Straits	28
13	Nitrogen and Chlorophyll - Tributary Streams	31
14	Observed Organic-Nitrogen and Chlorophyll Concentration	32
15	Predicted Nitrogen - Chlorophyll Ratio	33
16	Projected Chlorophyll Concentrations	33
17	Predicted Diurnal Dissolved Oxygen Variations	36
18	Miscellaneous - Light Distribution	38
19	Diurnal Dissolved Oxygen Variations (Predicted and Observed)	41
20	Predicted DO Values, 25 Foot Channel Using Basic Model	42
21	Predicted Dissolved Oxygen - Chlorophyll Relationship	45

LIST OF FIGURES (Continued)

Figure No.	Title	Following Page
22	Oxygen Consumption and Dissolved Oxygen	49
23	Dissolved Oxygen and Avoidance	50
24	Food Web Relationships - Striped Bass	51
25	Predicted Fishery Survival	56
26	Striped Bass - Length, Weight and Age Relationship	57
27	Seasonal Distribution of Adult Striped Bass in San Francisco Bay and Delta	58
28	Seasonal Migration Patterns of the Three King Salmon Runs in the Sacramento - San Joaquin River System	61
29	Relative Fish Populations vs Chlorophyll	66
30	Projected Fishery Detriments	67

Fold Out Map - North San Francisco Bay and Delta — Back of Report

I. INTRODUCTION

PURPOSE

The U. S. Bureau of Reclamation and the California Department of Water Resources jointly plan to construct a master drain in the San Joaquin Valley for the purpose of collecting and transporting highly saline agricultural drainage waters to a disposal point in the Sacramento - San Joaquin Delta near the City of Antioch.* While there is general agreement that such a drainage project will be required to permit the important agricultural economy of the San Joaquin Valley to continue to prosper, there is less agreement as to the resulting effects on the quality of Delta and San Francisco Bay waters of this plan for disposal. This stems in a large measure from a lack of information on which to base predictions of future water quality in this Bay-Delta tidal system and on how this quality would be affected by the addition of large quantities of agricultural drainage.

From its inception late in 1965 the Central Pacific Basins Comprehensive Water Pollution Control Project of the Federal Water Pollution Control Administration (FWPCA) has devoted its resources to a detailed investigation of this complex problem. Because of the necessity for developing information rapidly so as to avoid unnecessary delay of this important project, the investigation was limited in duration and was completed in December 1966, and the findings published in a summary report entitled "San Joaquin Master Drain - Effects on Water Quality of San Francisco Bay and Delta," dated January 1967. A four part Appendix contains details of investigative methods employed. The four parts are:

PART A - PROJECTED POPULATION, EMPLOYMENT AND WASTE LOADS
PART B - FUTURE WATER QUALITY
PART C - NUTRIENTS AND BIOLOGICAL RESPONSE
PART D - PESTICIDES

The purpose of the following report is to describe items appropriate to Appendix - PART C - Nutrients and Biological Response. Included in the descriptions are relationships, data, assumptions, and methodology leading to conclusions involving the effect of increased nutrients on San Francisco Bay and Delta waters and biota.

SCOPE OF THE INVESTIGATION

To predict the effect of the San Joaquin Master Drain on the quality of the Bay and Delta waters, it is necessary to consider it in the context of all other conditions affecting water quality that will exist in the future. This investigation, therefore, has taken into consideration:

1. The future development of the economy of the tributary area,
2. Expected changes in the quantity and quality of all waste water sources,

---

*The proposed joint state-federal drainage facility has been abandoned and a federal drain (The San Luis Drain) is currently contemplated. This decision was reached after the work described in this report was completed but before the publication of this Appendix.

3. Planned water resource development projects as they will affect the hydrology of the area, and

4. The uses of Bay and Delta waters that will be required in the future for all legitimate purposes.

The future fifty year period, 1970-2020, was examined. All existing information on water requirements, water quality, and pollution problems have been utilized to the maximum possible extent. Laboratory investigations, field studies, and engineering analyses were carried out only to the extent that new information was believed to be necessary for a satisfactory evaluation of present and future conditions. In general, laboratory and field studies were confined to special problems related to evaluation of the effects of nutrients and pesticides and to the study of dispersion characteristics in the receiving waters. The major project effort was devoted to the evaluation and interpretation of available information using, in some cases, special analytical techniques, such as mathematical models, developed for the purpose.

A number of possible plans for the non-pollutional discharge of the San Joaquin Master Drain were considered. The benefits and detriments of each plan were considered and a course of action selected that would adequately protect the quality of the receiving waters.

The scope of this part of the Appendix is limited to description of effects related to nutrient enrichment of the San Francisco Bay-Delta system including effects on fishery, recreation and shoreline real estate values. Material is presented describing laboratory and field studies, literature surveys on fishery resources and water quality requirements, Bay-Delta water quality and biota, and predictive models leading to economic evaluations.

The efforts of the Central Pacific Basins Project (CPBP) were supplemented to a significant degree by the special studies of nutrients, biological response, ecology, recreation and fisheries listed below. These investigations were carried out under contract to the Project in most cases with the participation and assistance of the Project staff.

1.	Mr. John Skinner, California Department of Fish and Game	Evaluation of Historical, Present and Future Commercial and Sport Fishery and Wildlife Resources of the Bay-Delta System
2.	Prof. David I. Jenkins Univ. of California, Berkeley	A Study of Methods Suitable for the Analysis & Preservation of Nitrogen Forms and Phosphorus Forms in an Estuarine Environment
3.	Prof. Robert Selleck Univ. of California, Berkeley	Laboratory Experiments on Effects of Nutrients on the Primary Productivity of San Francisco Bay

4. Dr. E. G. Altouney Stanford Research Institute	Recreation and Fishery Values in the San Francisco Bay and Delta
5. Dr. Ray B. Krone Consultant on Estuarial Sediments	Estimation of Future Amount and Nature of Suspended Sediments in Waters of the San Francisco Bay System
6. Dr. James B. Lackey Biological Consultant	Assessment of the Effects of Increased Nutrients on the Ecology of San Francisco Bay-Delta System

AUTHORITY

The Federal Water Pollution Control Administration is the agency of the Federal government having primary responsibility for implementation of a national policy for enhancement of the quality of the nation's water resources through the control of pollution. This policy has been spelled out in a series of legislative acts over the past decade which are described collectively as the Federal Water Pollution Control Act, as amended (33 USC 466a et seq.). Section 3 of this Act calls for the development of comprehensive programs for the control of water pollution in the major interstate river basins of the nation.

The Central Pacific Basins Project was established for this purpose and carried out this investigation as its initial step in meeting the objective of a comprehensive program for pollution control in its area of responsibility.

The FWPCA has, in addition, the responsibility for review and evaluation of all federal water resource development projects for their impact on water quality in accordance with established federal inter-agency procedures. This responsibility has broadened by Executive Order 11288 dated July 7, 1966 which describes procedures for the prevention, control, and abatement of water pollution by Federal activities and installations, such as the proposed San Joaquin Master Drain.

ACKNOWLEDGMENTS

Experiments described are principally those carried out under Purchase Order Agreements between Dr. Robert Selleck, University of California, Berkeley and FWPCA, CPBP, Alameda, California. Most of the analytical chemical work was performed by Paul Graham, Chemist, working under the direction of Dr. David I. Jenkins, Sanitary Engineering Research Laboratory (SERL), University of California, Richmond, California.

Chlorophyll determinations and microscopic evaluations were carried out by the project staff with technical assistance from Robert Minnehan and Jesse Ante, FWPCA and Steven Chaum, SERL. Mathematical evaluations were carried out by project staff with special assistance from Robert Minnehan, engineering economist and Alan Fabrick, student aid.

Ecosystem tanks were made available by SERL through agreements with Drs. Goulke and Oswald. Their cooperation and the assistance of Henry Gee with certain piping and pumping arrangements is gratefully acknowledged.

Data on chlorophyll levels in Suisun Bay and the San Joaquin River were made available by the California Department of Fish and Game, Stockton. Permission to use these data is gratefully acknowledged.

Tide flat studies were carried out under the guidance of Dr. James B. Lackey, consultant on the biology of water and wastes, who also served as a consultant to the study on effects of nutrient enrichment of San Francisco Bay and Delta waters.

II. SUMMARY OF FINDINGS AND CONCLUSIONS

FINDINGS

1. Nitrogen and phosphorus sources from wastes and streams tributary to San Pablo and Suisun Bays and the Western Delta are currently estimated as 70,500 pounds total nitrogen and 14,600 pounds total phosphorus per day. These values are expected to increase to three fold by 1990 and four to six fold by 2020.

2. Additional nitrogen loadings projected for the San Joaquin Master Drain are 84,100 and 115,300 pounds per day for 1990 and 2020 respectively.

3. Total nitrogen concentrations in the main water mass of the northern portion of San Francisco Bay and the Delta currently ranges from less than 1 mg/l in the Central Bay and Central Delta to between 1 and 2 mg/l in Suisun Bay and the Western Delta during the summer season. Total phosphorus concentration are generally between 0.1 and 0.3 mg/l in these waters.

4. Dissolved silica concentrations are known to vary seasonally from about 20 mg/l in the tributary streams to less than 1 mg/l in parts of Suisun Bay at times during summer.

5. Maximum phytoplankton populations occur in Suisun Bay and the Western Delta. Lesser phytoplankton crops are found in the more marine areas of the north Bay system and in the fresh water Central Delta area. Phytoplankton populations in the Suisun Bay and the Western Delta increase rapidly during the spring months and peak populations have been observed during June and July.

6. Minimum inorganic nitrogen concentrations are observed during late spring and early summer in Suisun Bay and the Western Delta, where apparent nitrate and ammonia depletion have occurred in several locations. Laboratory and field-incubated bioassays of Bay and Western Delta waters yielded higher algal crops with inorganic nitrogen stimulation.

7. The waters of the main water mass of the North San Francisco Bay and Delta system are well oxygenated and, though turbid, are generally free from nuisance.

8. Reductions in Delta outflow caused by storage and diversions of river water to the South are expected to reduce median annual sediment transport to the Bay from approximately 2.6 million tons at present to 0.7 and 0.4 million tons in 1990 and 2020 respectively.

9. Certain enriched tidal streams and flats tributary to the main water mass are known to support nuisance levels of algae as characterized by discolored waters, stranded decaying vegetation, and dissolved oxygen fluctuations.

10. The North Bay and Delta waters support many beneficial water uses including sport and commercial fishing, boating, hunting and other recreational activities as well as aesthetic enjoyment by visitors and property owners with shoreline or vista opportunities.

CONCLUSIONS

1. Nitrogen is the most probable limiting element important to algal nutrition in the waters of Suisun Bay and the Western Delta in the general vicinity of the proposed Drain discharge.

2. The combined effect of reduced freshwater flow and reduced sediment transport from the river systems to the Bay-Delta system will reduce suspended inorganic sediment concentrations and permit light energy to penetrate deeper into Bay waters except during periods when plankton significantly affect water clarity.

3. The combined effect of nutrient enrichment and sediment inflow reduction is expected to lead to higher algal populations in Suisun Bay and the Western Delta in the future. Possible seasonal dissolved silica depletions due to increased diatom growth may lead to a shift in algal population types from diatoms to algae which do not form silica shells.

4. The projected eutrophication of Suisun Bay and Western Delta waters is expected to lead to dissolved oxygen depressions in the deeper regions and nuisance green seaweed growth on tidal flats having suitable substrates during the May-October period, particularly under sustained low outflow conditions.

5. Populations of the anadromous striped bass, king salmon and American shad are predicted to decline as a result of exposure to depressed oxygen levels anticipated in Suisun Bay-Western Delta waters.

6. Annual anadromous fishery-related detriments are estimated to reach 4.4-9.1 million dollars in 1990 and 8.0-12.4 million dollars in 2020.

7. Detriments to shoreline property, boating, recreation, aesthetics and wildlife propagation and sustenance attributable to enrichment by the San Joaquin Master Drain are estimated to reach 7-17 million dollars annually by 2020.

8. Potential nutrient enrichment associated detriments could be prevented if algal densities are controlled such that the chlorophyll content of the waters of Suisun Bay and the Western Delta is maintained below 100 µg/l during the dry weather season. This objective should be achieved if the total nitrogen concentration is maintained below 2 mg/l. Fresh water reaches of the Delta may require a lower nitrogen limit to prevent possible blue green algal nuisances under minimum outflow conditions.

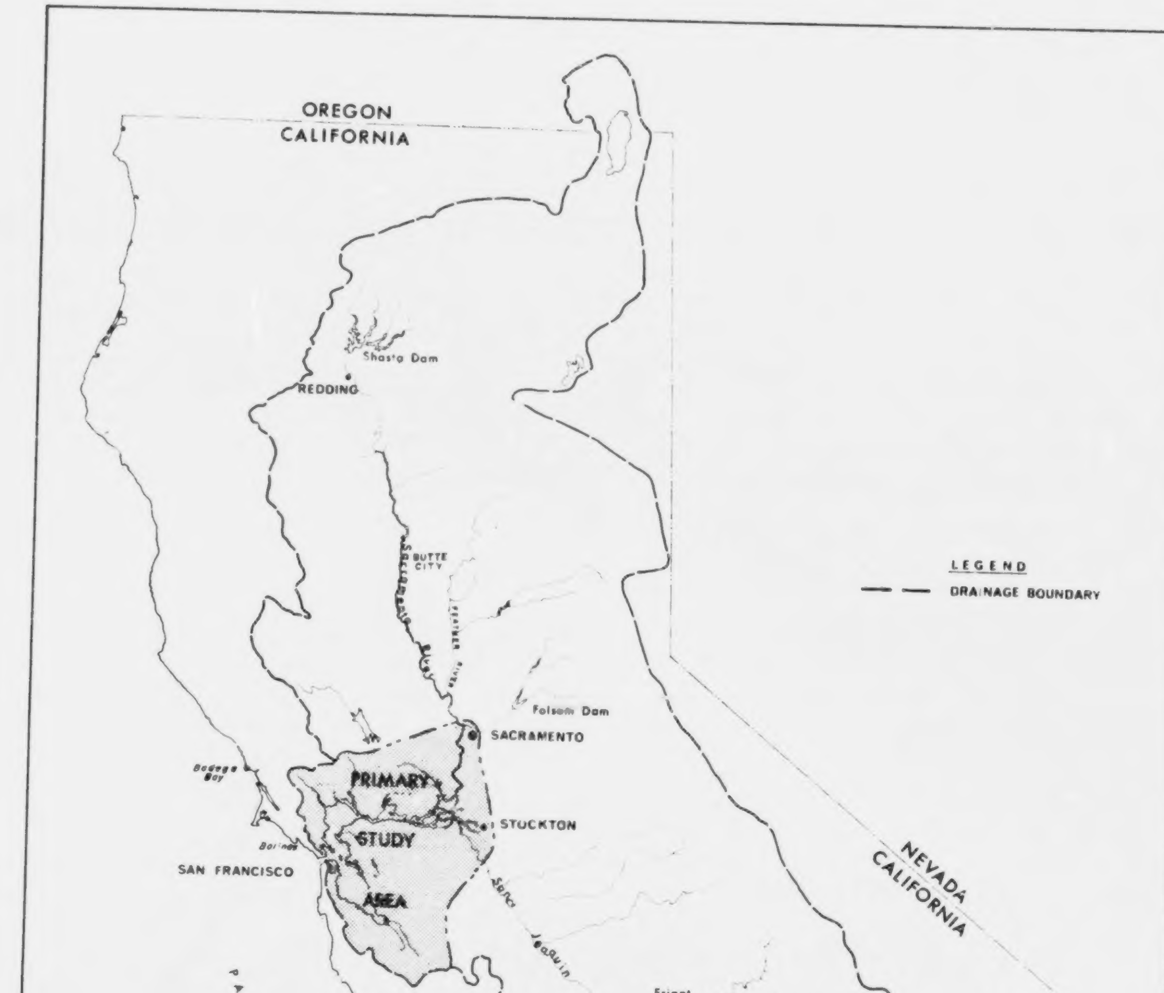
III. DESCRIPTION OF THE STUDY

DESCRIPTION OF STUDY AREA

The Central Valley Basin of California (See Figure 1) is drained by two major river systems, the Sacramento River on the north and the San Joaquin River on the south. The combined basin extends nearly 500 miles in a northwest-southeast direction and averages 120 miles in width. It includes more than one-third of California and covers some 64,000 square miles. The basin is entirely surrounded by mountains except for a narrow gap in its western edge through which the combined Sacramento-San Joaquin Rivers flow to the Pacific Ocean through the San Francisco Bay. The Valley floor is a gently sloping alluvial plain that comprises nearly a third of the total basin area. It is about 400 miles long and averages about 45 miles in width. On the valley floor are 10,300,000 acres of prime agricultural land of which approximately one-half is currently under irrigation.

The climate of the Central Valley varies widely from the warm, two season climate of the valley floor to the colder, four season climate of the Sierra Nevada. On the valley floor, about 90 percent of the rainfall occurs from November to April, while the summers are hot and dry. The San Joaquin River Basin receives considerably less rainfall and has much less surface runoff than the Sacramento River Basin. Since climate and soil conditions are very favorable to irrigated agriculture, ground waters and local surface waters in the San Joaquin Valley have been used to their capacity for this purpose. The southern half of the San Joaquin Valley (Tulare Lake Basin) has no natural drainage outlet. This area contains 4.8 million acres of irrigable land while the remaining portion of the San Joaquin Valley to the north contains 3.2 million acres of irrigable land. Approximately 3.9 million acres in the San Joaquin Valley are presently irrigated.

The Sacramento - San Joaquin Delta is located at the confluence of the Sacramento and San Joaquin Rivers system. The Delta contains some 738,000 acres, interlaced with 700 miles of meandering waterways covering 50,000 acres. Over 500,000 acres of agricultural lands are irrigated in the Delta and these comprise some of the most productive in California. About 415,000 acres, known as the Delta Lowlands, lie between elevations of 5 feet above and 20 feet below sea level. This area is composed of peat, organic sediments, and alluvium, and is protected from flood waters and high tides by man-made levees. Waters flowing out of the Delta pass through Suisun Bay, San Pablo Bay, North San Francisco Bay, and finally through the Golden Gate to the Pacific Ocean. This entire area, including the Delta is subject to tidal action.


OREGON
CALIFORNIA
Shasta Dam
REDDING
BUTTE CITY
Sacramento River
Feather River
Folsom Dam
SACRAMENTO
Bodega Bay
PRIMARY STUDY AREA
STOCKTON
Bolinas
SAN FRANCISCO
San Joaquin River
Friant Dam
Mendota Pool
FRESNO
Tulare Lake Bed
BAKERSFIELD
PACIFIC OCEAN
NEVADA
CALIFORNIA
LEGEND
DRAINAGE BOUNDARY
SCALE IN MILES
16 8 0 16 32 48 64 80

CENTRAL PACIFIC BASINS PROJECT

STUDY AREA

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SOUTHWEST REGION SAN FRANCISCO, CALIFORNIA

8-17

FIGURE 1

The primary study area of this investigation is shown in Figure 2. It includes the Sacramento - San Joaquin Delta, Suisun Bay, San Pablo Bay and San Francisco Bay

Particular emphasis was placed on these waters since they represent the primary area that would be influenced by the proposed discharge of the San Joaquin Master Drain. In addition, attention was directed to the Central Valley to the extent that activities there would influence water quality conditions in the San Francisco Bay and Delta.

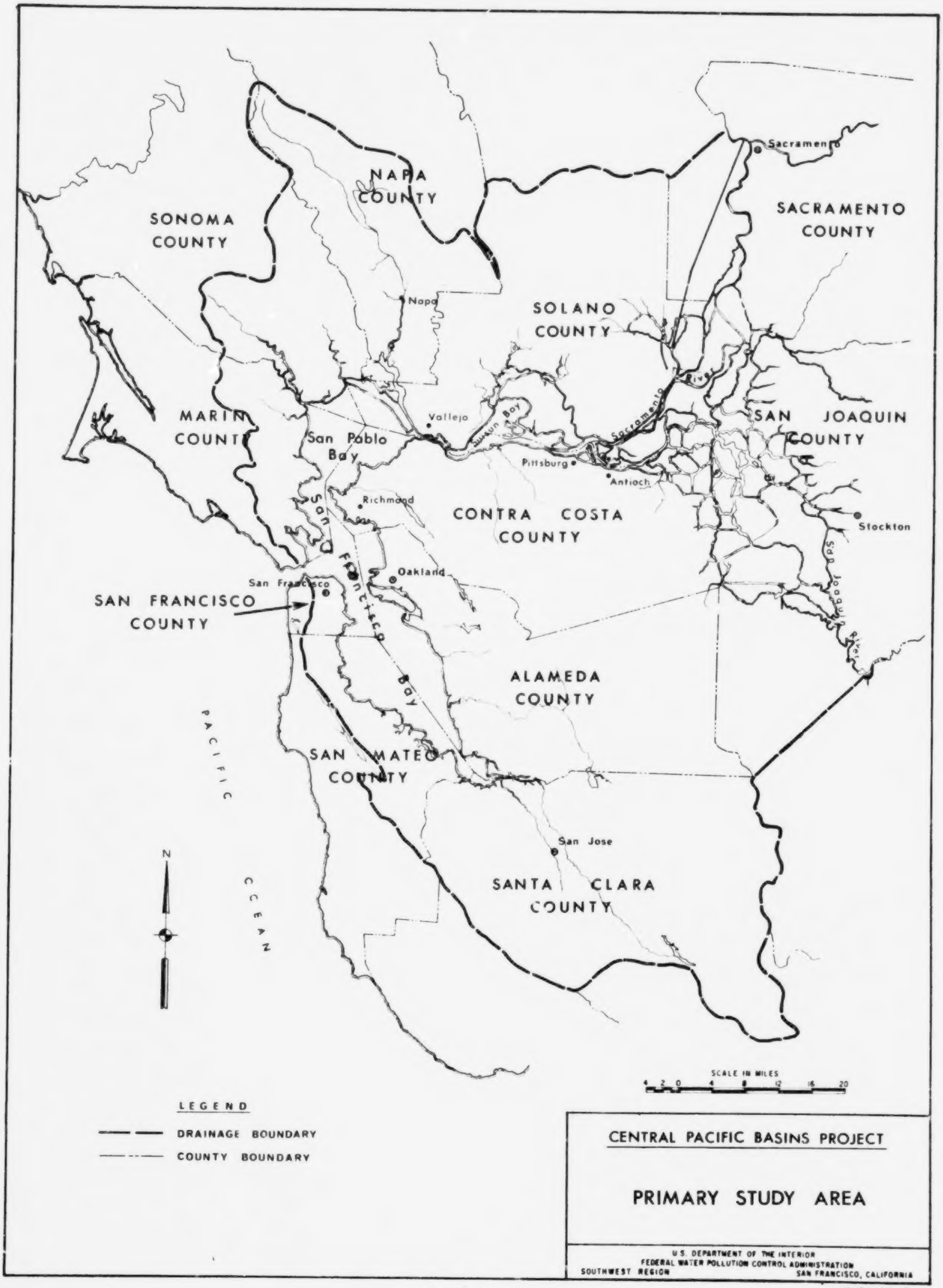
Many large inter-basin water transfers, both existing and planned, use the channels of the Delta to effect the transfer of water from the Sacramento basin to San Joaquin Valley. This cross-delta flow of water sumper-imposed upon tidal currents, and a net outflow seaward, creates a most complex hydrological situation that significantly affects the quality of water found in the Delta. These waters would be most directly affected by the proposed Master Drain discharge. In addition, the quality of San Francisco Bay waters is greatly influenced by the amount of outflow from the Detla.

SAN JOAQUIN MASTER DRAIN

The ultimate need for drainage from a large area of agricultural lands in the San Joaquin Valley was recognized late in the last centruy, but only within the last ten or fifteen years were serious efforts made to accomplish this objective. After hearings in 1956, a State Legislative Committee concluded that agricultural drainage problems existed and were becoming more serious in the Valley. The California Department of Water Resources initiated the San Joaquin Valley Drainage Investigation in 1957 and three years later the Burns-Porter Act authorized San Joaquin Valley drainage facilities as part of the California Water Plan.

Simultaneously, Congressional hearings on the San Luis Unit of the Central Valley Project resulted in the inclusion of drainage provisions in the authorizing legislation, Public Law 86-488, passed in June 1960. This Act required that construction of the San Luis Unit not commence until provision had been made for an interceptor drain to the Delta or until satisfactory assurance had been received that the State of California would provide a master drain for the San Joaquin Valley that would adequately serve the San Luis Unit. The Bureau of Reclamation subsequently developed plans for a San Luis Interceptor Drain.

After first considering separate drains, studies initiated jointly by the Bureau of Reclamation and the California Department of Water Resources in 1963 revealed that significant economies would result from construction of a single Master Drain serving the Federal San Luis service area as well as other areas of the San Joaquin Valley. The joint drain facility, known as the San Joaquin Master Drain, was described in Bulletin No. 127 which was published in January 1965 by


NAPA COUNTY
SONOMA COUNTY
SACRAMENTO COUNTY
Sacramento
SOLANO COUNTY
Napa
MARIN COUNTY
San Pablo Bay
Vallejo
Suisun Bay
Sacramento River
SAN JOAQUIN COUNTY
Pittsburg
Antioch
Richmond
CONTRA COSTA COUNTY
Stockton
San Joaquin River
San Francisco Bay
Oakland
San Francisco
SAN FRANCISCO COUNTY
ALAMEDA COUNTY
PACIFIC OCEAN
SAN MATEO COUNTY
San Jose
SANTA CLARA COUNTY
N
SCALE IN MILES
4 2 0 4 8 12 16 20
LEGEND
DRAINAGE BOUNDARY
COUNTY BOUNDARY

CENTRAL PACIFIC BASINS PROJECT

PRIMARY STUDY AREA

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SOUTHWEST REGION SAN FRANCISCO, CALIFORNIA

FIGURE 2

the California Department of Water Resources. This report considered the costs of a number of disposal schemes and recommended that the drain be discharged to the San Joaquin River near the City of Antioch. Figure 3 shows the principal routes considered. The recommended discharge point was the least costly of those considered. While considerable data had been gathered on the probable quantity and quality of the drain waters, little information was available concerning the effects of this drainage on receiving water quality.

The San Joaquin Master Drain as presently planned would be about 280 miles in length and would have a capacity at its southern end of 60 cubic feet per second and a terminal capacity at the northern end of 900 cubic feet per second. The annual volume of waste water conveyed would reach approximately 500,000 acre feet by the year 2000. Construction would be accomplished in several stages. The first stage would be constructed from Kettleman City to Antioch and would have a capacity of 120 cubic feet per second at its southern end and 400 cubic feet per second at its terminus. This stage would be in full operation by mid-1970. By 1990 the initial stage would be expanded to a capacity of 270 cubic feet per second at Kettleman City and 900 cubic feet per second at the terminus. A further extension of the drain southward into Kern County would be in operation after 1975. See Figure 3 for locations described above.

The Master Drain will carry large amounts of nutrient materials (particularly nitrogen), pesticides and salts. Municipal and industrial wastes discharged directly to the Bay-Delta system or into tributary streams will furnish additional nutrients including both nitrogen and phosphorus. The present and projected nitrogen and phosphorus loads for the year 1990 and 2020 are contained in Table 1.

TABLE 1

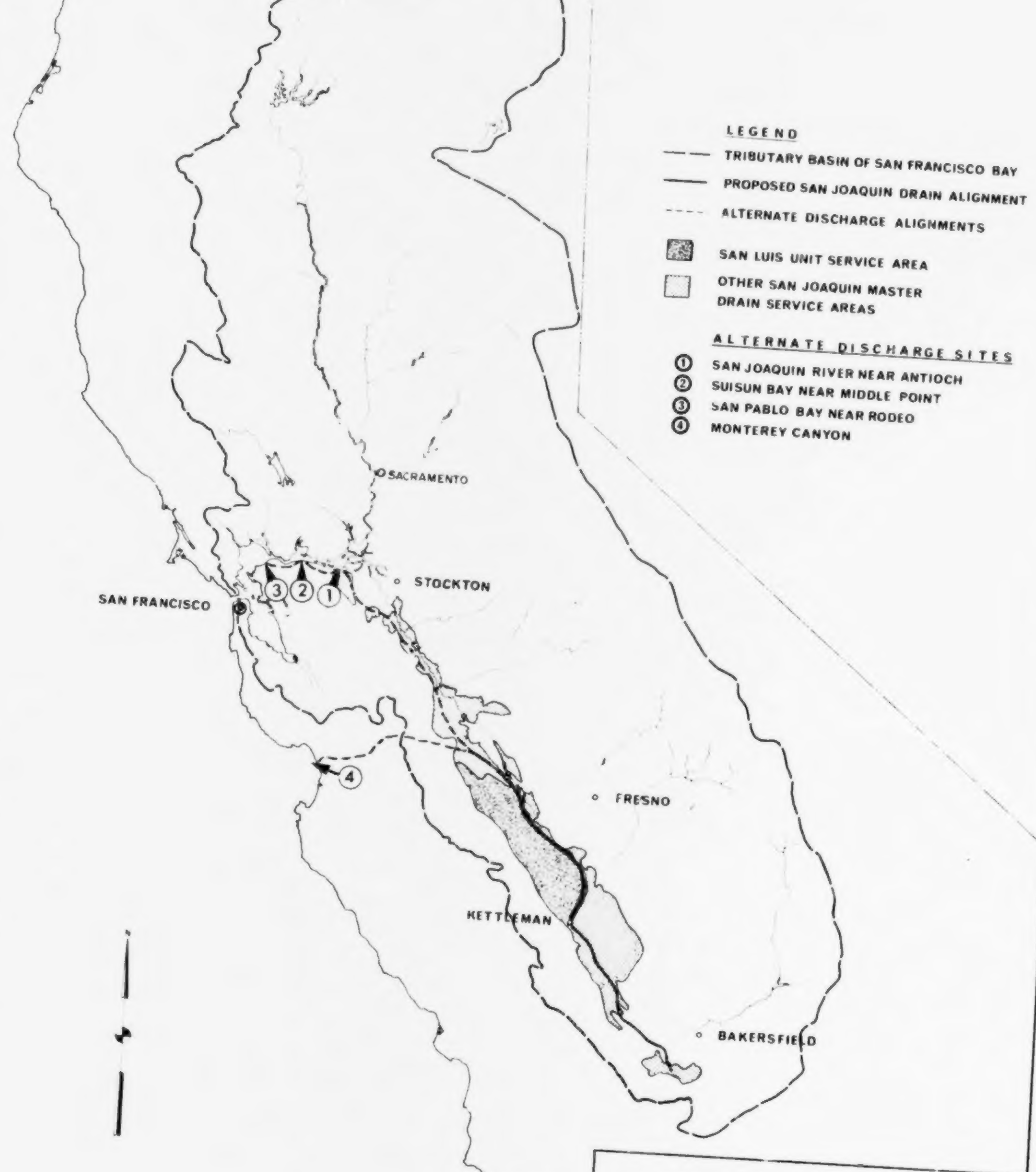
SUMMARY OF NITROGEN AND PHOSPHORUS INPUTS (a)

SAN PABLO BAY, SUISUN BAY AND THE DELTA

SUMMER CONDITIONS

	Nitrogen 1000 lb./day			Phosphorus 1000 lb./day		
	Present	1990	2020	Present	1990	2020
Municipal	24.3	58.6	117.2	8.7	25.8	53.3
Industrial	33.1	48.2	62.1	0.4	1.0	1.6
Tributary Stream	13.1	54.1	103.0	5.5	15.4	34.2
San Joaquin Drain	----	84.1	115.3	---	0.4	0.6
Totals	70.5	245.0	397.6	14.6	42.6	89.7

(a) A portion of the nitrogen and phosphorus from tributary streams will not enter the Bay-Delta system in the future due to planned transfer via the Peripheral Canal. This has been considered in the analyses of the effects of waste discharges on the Bay-Delta system.


LEGEND
TRIBUTARY BASIN OF SAN FRANCISCO BAY
PROPOSED SAN JOAQUIN DRAIN ALIGNMENT
ALTERNATE DISCHARGE ALIGNMENTS
▨ SAN LUIS UNIT SERVICE AREA
☐ OTHER SAN JOAQUIN MASTER DRAIN SERVICE AREAS
ALTERNATE DISCHARGE SITES
① SAN JOAQUIN RIVER NEAR ANTIOCH
② SUISUN BAY NEAR MIDDLE POINT
③ SAN PABLO BAY NEAR RODEO
④ MONTEREY CANYON
SACRAMENTO
STOCKTON
SAN FRANCISCO
③
②
①
④
FRESNO
KETTLEMAN
BAKERSFIELD
N
SCALE IN MILES
16 8 0 16 32 48 64 80

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SAN JOAQUIN DRAINAGE AREA AND ALTERNATE DISCHARGE SITES

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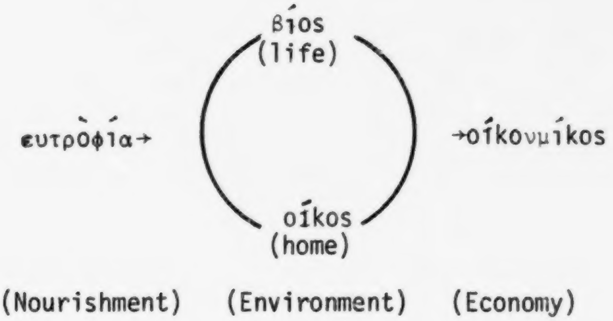
FIGURE 3

IV. WATER QUALITY AND BIOLOGICAL RELATIONSHIP

Life requires nutrition. In addition, plants require light energy to synthesize inorganic nutrients to living tissue. In temperate aquatic environments the availability of nutrients and light usually determines how much life can be supported.

The basic question of the effect of increasing nutrient levels (eutrophication) on the Bay-Delta environment is considered in the balance of this report. The effects are related to economically beneficial water uses including fisheries (sport and commercial), wild fowl, recreation, boating, shoreline real estate and aesthetics.

The consequences of eutrophication may be expressed as follows:



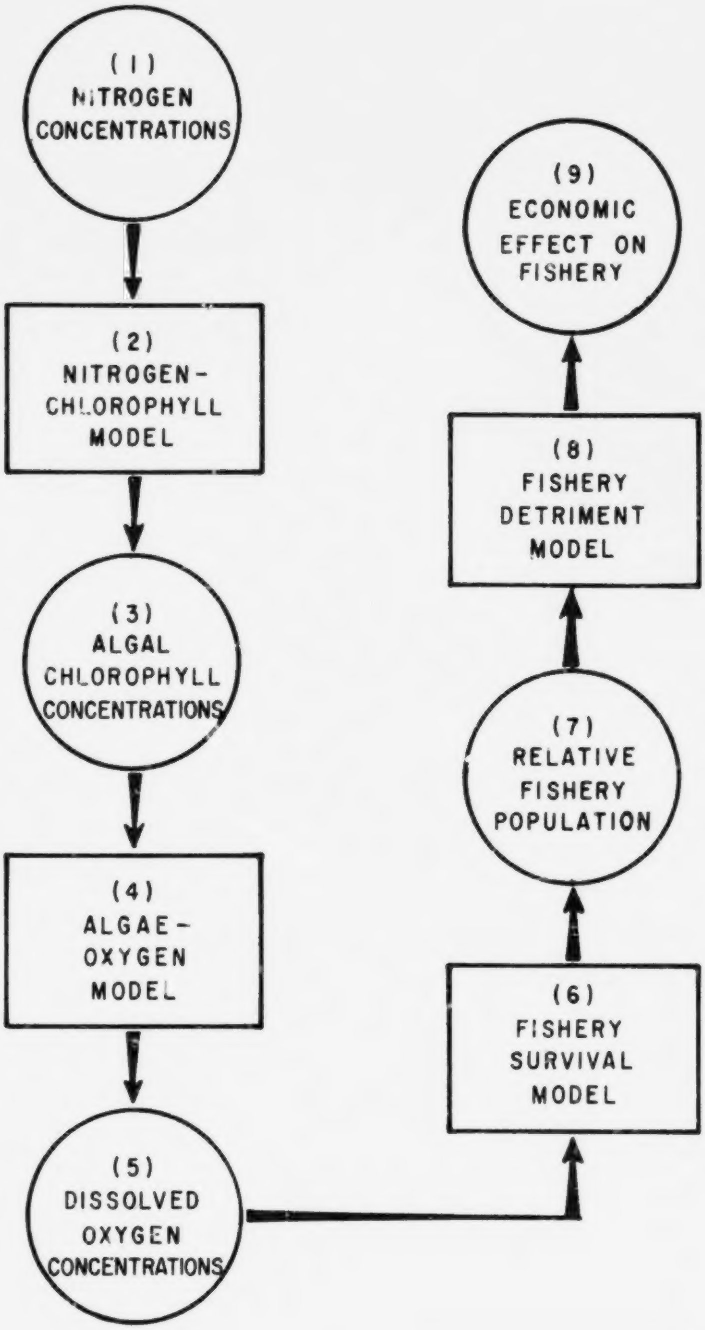
This expression says that nutrients have an effect on the aquatic environment (the ecology and the water quality) and the resulting environmental quality has an effect on the economic resources associated with the aquatic environment.

The steps in the evaluation of future fishery resource economic values associated with increased nutrient concentrations in the Suisun Bay - western Delta area resulting from San Joaquin Master Drain, urban and other wastes are charted on Figure 4. The components include four relationships, which may be posed as the four major questions regarding the effect of increased nutrients on fishery values.

1. Will increased nitrogen and phosphorus and reduced suspended sediment concentrations in Suisun Bay and the western waters of the Delta stimulate greater algal populations in the future?

2. What will be the effect of increased algal populations on water quality of the Suisun Bay - western Delta system?

3. What will be the effect of algal - induced changes in water quality on the fishery resources dependent upon Suisun Bay and western Delta waters?


(1) NITROGEN CONCENTRATIONS
(2) NITROGEN-CHLOROPHYLL MODEL
(3) ALGAL CHLOROPHYLL CONCENTRATIONS
(4) ALGAE-OXYGEN MODEL
(5) DISSOLVED OXYGEN CONCENTRATIONS
(6) FISHERY SURVIVAL MODEL
(7) RELATIVE FISHERY POPULATION
(8) FISHERY DETRIMENT MODEL
(9) ECONOMIC EFFECT ON FISHERY

CENTRAL PACIFIC BASINS PROJECT

COMPONENTS OF
FISHERY DETRIMENT
PREDICTIONS

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMINISTRATION
SOUTHWEST REGION SAN FRANCISCO, CALIFORNIA

FIGURE 4

4. What will be the economic consequences associated with changes in the fishery resources?

These questions and similar questions relating to the other water uses are considered in an analysis of each component based on relationships developed from limnology, oceanography, biology and sanitary engineering literature, water quality data from the Bay and Delta and other estuaries, laboratory and field experiments using Bay and Delta waters, mathematical model applications including use of a digital computer (IBM 7094) and economic valuation techniques based on Senate Document 97 Supplement 1, and economic values of recreational water uses (including fisheries) developed by Stanford Research Institute.

The term "model," as used in this report, refers to any formulation used for prediction purposes (1).

Ecology is the branch of science which deals with the relationship between living things and their environment. Relationships between nutrients, light, temperature, and living populations are described in this report. These descriptions apply generally to the San Francisco Bay and Delta. Data are included on present water quality and biological conditions in San Francisco Bay and Delta waters.

A fold out map is provided at the back of this report to acquaint the reader with the many locations described in the text.

PRIMARY PRODUCTION AND NUTRIENTS

Nutrient materials and solar energy give life to the estuary through primary production. Nutrients include forms of the elements carbon, nitrogen and phosphorus. Other elements and compounds are essential in lesser concentrations including trace elements, vitamins and (for some plant groups) dissolved silica.

Primary Production

Primary production (photosynthesis) may be described by the following expression:

$$1.3\text{x}10^{6}\text{Cal.}+106\ CO_2+90H_2O+16NO_3+1\ PO_4+\text{Mineral elements} = \text{(Radiant Energy)}$$

$$+\underset{\text{(Potential Energy)}}{\text{(13,000 Cal. in 3258 gms of Protoplasm)*}}+154O_2+\underset{\text{(Heat Energy Dispersal)}}{1.287\text{x}10^{6}\text{Calories}}$$

* (106 C, 180H, 46, 0, 16N, 1P, 815 gms mineral ash)

The above expression which more completely describes the photosynthetic phenomenon may be simplified to read:

$$CO_2+H_2O = \underset{\text{(Bios)}}{CH_2O+02}$$

The bio-synthesis of inorganic matter is, however, more complex than either of the above.

Based on major elemental composition an alga could be expressed in the following ways:

$C_{100} H_{251} O_{48}$	(Diatoms after Brandt and Rabin)
$C_{100} H_{170} O_{65}$	(Ulva after Brandt and Rabin)
$C_{100} H_{168} O_{41}$	(Chlorella after Ketchum and Redfield)
$C_{100} H_{165} O_{45} N_{16}$	(Chlorella after Spoeke and Milner)

The elemental composition of some aquatic plants is shown in Table 2. Ratios of carbon (C), nitrogen (N) and phosphorus (P) to chlorophyll (α) are shown in Table 3.

TABLE 2

ELEMENTARY COMPOSITION

MARINE PHYTOPLANKTON (a)

(% Ash Free Dry Weight)
+ Standard Deviation

ALGAL GROUP	ELEMENT		
	C	N	P
Diatoms (a)	50.5 (±3.9)	7.0 (±3.7)	1.5 (±0.9)
Green Algae (a)	54.5 (±1.3)	7.7 (±0.6)	2.9 (±0.8)
Dinoflagellates (a)	48.1 (±1.9)	10.4 (±1.4)	0.8 (±0.4)

(a) After Ryther, John H., Limnology and Oceanography, 1 (a) 1956.

TABLE 3

RATIOS INVOLVING CHLOROPHYLL (α)
(Diatoms)(a)(b)

GENUS	C/α	N/α	P/α
Chaetoceros	44	8	2.1
Skeletonema	26	6	1.7
Coscinodiscus	69	12	1.7
Phaeodactylum	26	4	1.4
Skeletonema (High N)	25	4.5	1.0
Skeletonema (N Deficient)	68	4.3	---

a) McAllister et al., J. Fishery Res. Board Canada, 21 (1) 1964.

b) Parsons et al., J. Fishery Res. Board Canada, 18 (6) 1961.

Data such as the above may be used to establish the upper limit of algal growth possible for a given level of nutrition.

Carbon

Carbon is present in natural waters as carbon dioxide (CO_2), carbonate (CO_3), biocarbonate (HCO_3) and organic carbon.

Most of the CO_2 present in seawater (pH ∿ 8.0) is bound in bicarbonate and carbonate (chiefly bicarbonate) ions. Atmospheric reaeration of CO_2 is an unimportant carbon source. Carbon dioxide is removed from solution by the photosynthetic process. A lowering of CO_2 (representing a rise in pH) results in an increase of CO_3 ions and progressive loss of HCO_3 ions.

The waters of the Bay-Delta system contain substantial concentrations of bicarbonate and carbonate. Carbon is not a limiting element in the estuary.

Nitrogen

The nitrogen levels generally found in the open Bay waters vary with place and season. South San Francisco Bay, south of Dumbarton Bridge is higher in total nitrogen than any of the other major water masses, largely because of the nitrogen content of Coyote Creek which carries effluent from the City of San Jose. During 1966, total nitrogen levels in excess of 3 mg/l were found in the open Bay area south of Dumbarton Bridge and above 15 mg/l in Coyote Creek. Water quality problems (particularly low dissolved oxygen levels) have been evident in this area for years.

The north Bay area from the Golden Gate northward and eastward has generally lower nitrogen levels except in the smaller tributary estuaries and near waste outfalls. The Golden Gate Bridge area and Central San Francisco Bay usually has less than 0.75 mg/l total N. Upstream nitrogen levels are higher due to waste dischargers, lower dilution and the enriching effects of land drainage as contrasted with the more barren oceanic waters. The highest nitrogen concentrations in the open Bay north of the Bay Bridge are between Martinez and Antioch in Suisun Bay where there are many nitrogen dischargers. Total N in Suisun Bay ranges from 1.0 - 2.0 mg/l.

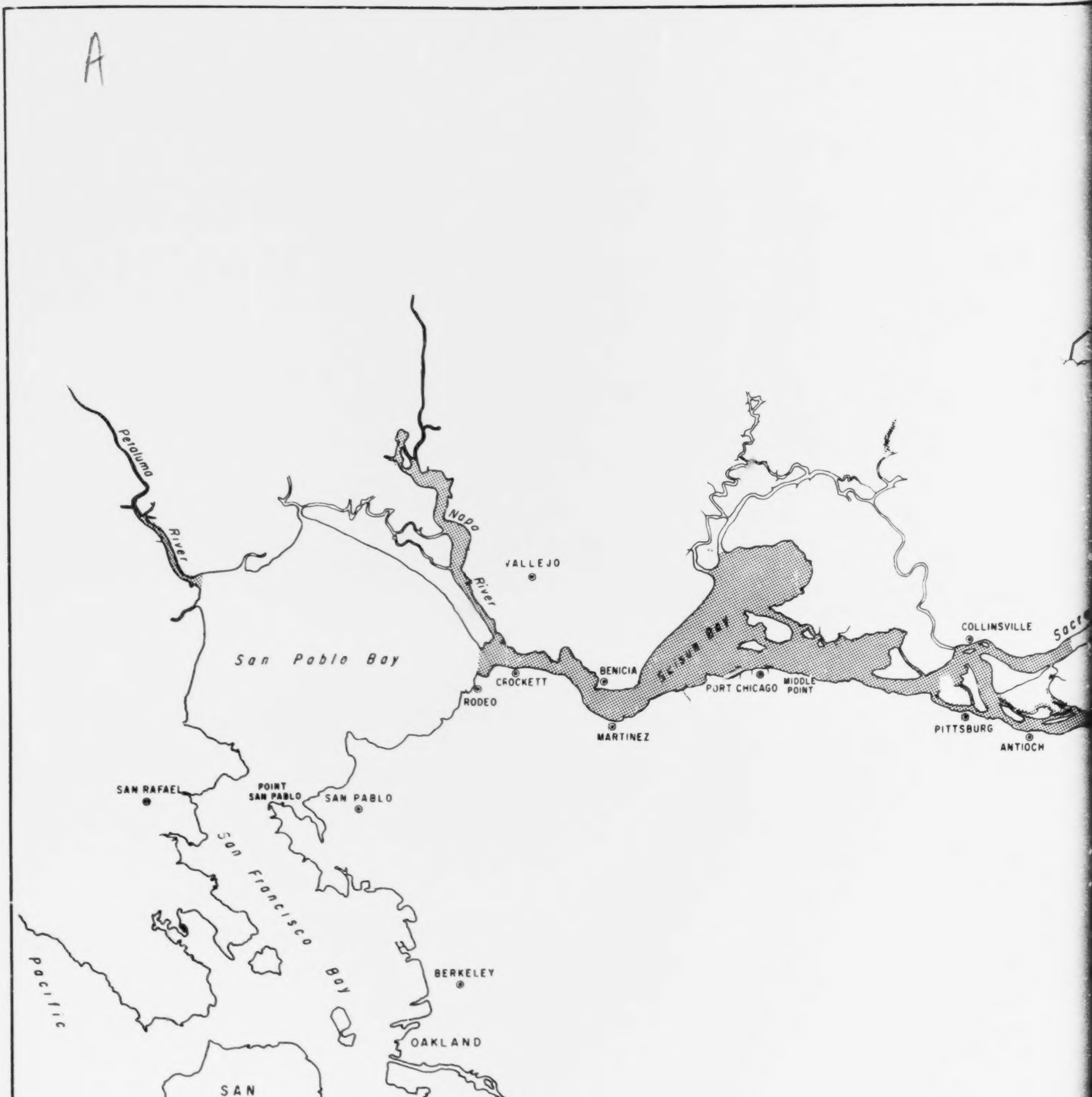
Total nitrogen concentrations are generally lower (less than 1 mg/l) through the Delta channels except in the south eastern Delta near Stockton where municipal-industrial wastes and agricultural return flows enrich the waters. Studies carried out in 1964 by USPHS (now FWPCA) and Central Valley Regional Water Quality Control Board personnel in the San Joaquin River near Stockton indicate total nitrogen concentrations typically exceed 2 mg/l during the late summer and early autumn months (2).

Figure 5 is a map depicting the total nitrogen distribution in the estuary as representative of present summer conditions.

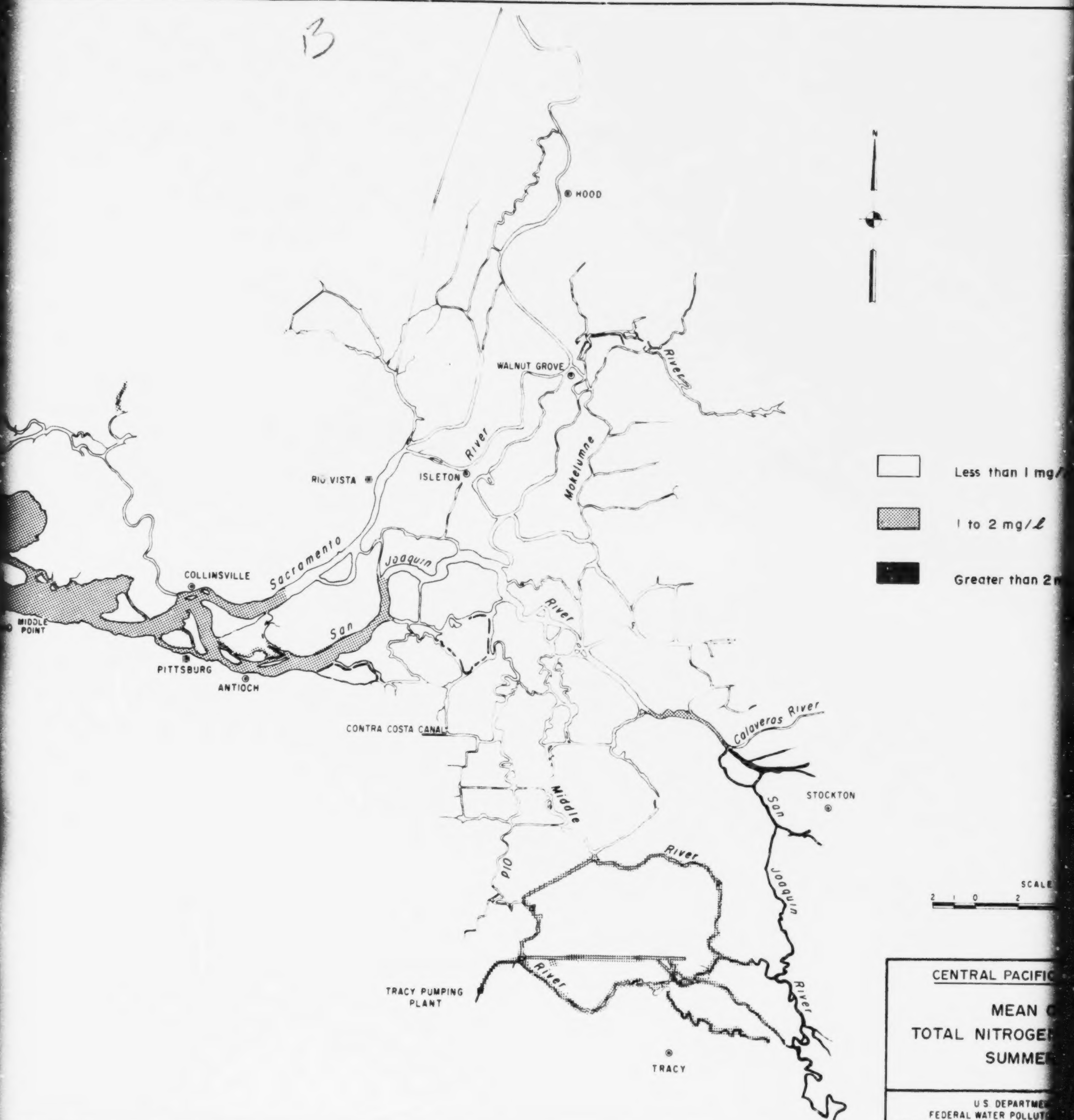
Nitrogen is present in a number of chemical stages including organic and inorganic forms. The nitrogen cycle in Bay-Delta waters, as in other natural waters, follows seasonal patterns. During times of low algal activity most of the total nitrogen as measured is present as nitrate-nitrogen. Waste materials entering Suisun Bay the year round contain all forms of nitrogen, however, many of the larger dischargers discharge principally ammonia nitrogen (NH_3-N). The ammonia is oxidized to nitrite (NO_2) and nitrate (NO_3) or utilized directly by algae. Laboratory studies by Metcalf and Eddy Consulting Engineers have demonstrated that ammonia added to Bay water is oxidized to nitrite in a reasonably short time (less than 16 days)(5). All ammonia spiked samples in these studies were oxidized to nitrate by the end of 30 days.

Studies by the FWPCA and University of California have described the change in nitrogen forms during the period of highest algal activity generally May-October. Sampling by the University of California at the

A


Petaluma River
Napa River
VALLEJO
San Pablo Bay
CROCKETT
RODEO
BENICIA
Suisun Bay
MARTINEZ
PORT CHICAGO
MIDDLE POINT
COLLINSVILLE
Sacr
PITTSBURG
ANTIOCH
SAN RAFAEL
POINT SAN PABLO
SAN PABLO
San Francisco Bay
BERKELEY
OAKLAND
SAN FRANCISCO
Pacific Ocean

13


N
HOOD
WALNUT GROVE
River
Mokelumne
RIO VISTA
ISLETON
River
Sacramento
COLLINSVILLE
Joaquin
San
River
MIDDLE POINT
PITTSBURG
ANTIOCH
CONTRA COSTA CANAL
Calaveras River
STOCKTON
San
Joaquin
River
Middle
Old
River
River
TRACY PUMPING PLANT
TRACY
▢ Less than 1 mg/
▨ 1 to 2 mg/ℓ
■ Greater than 2
SCALE
2 1 0 2

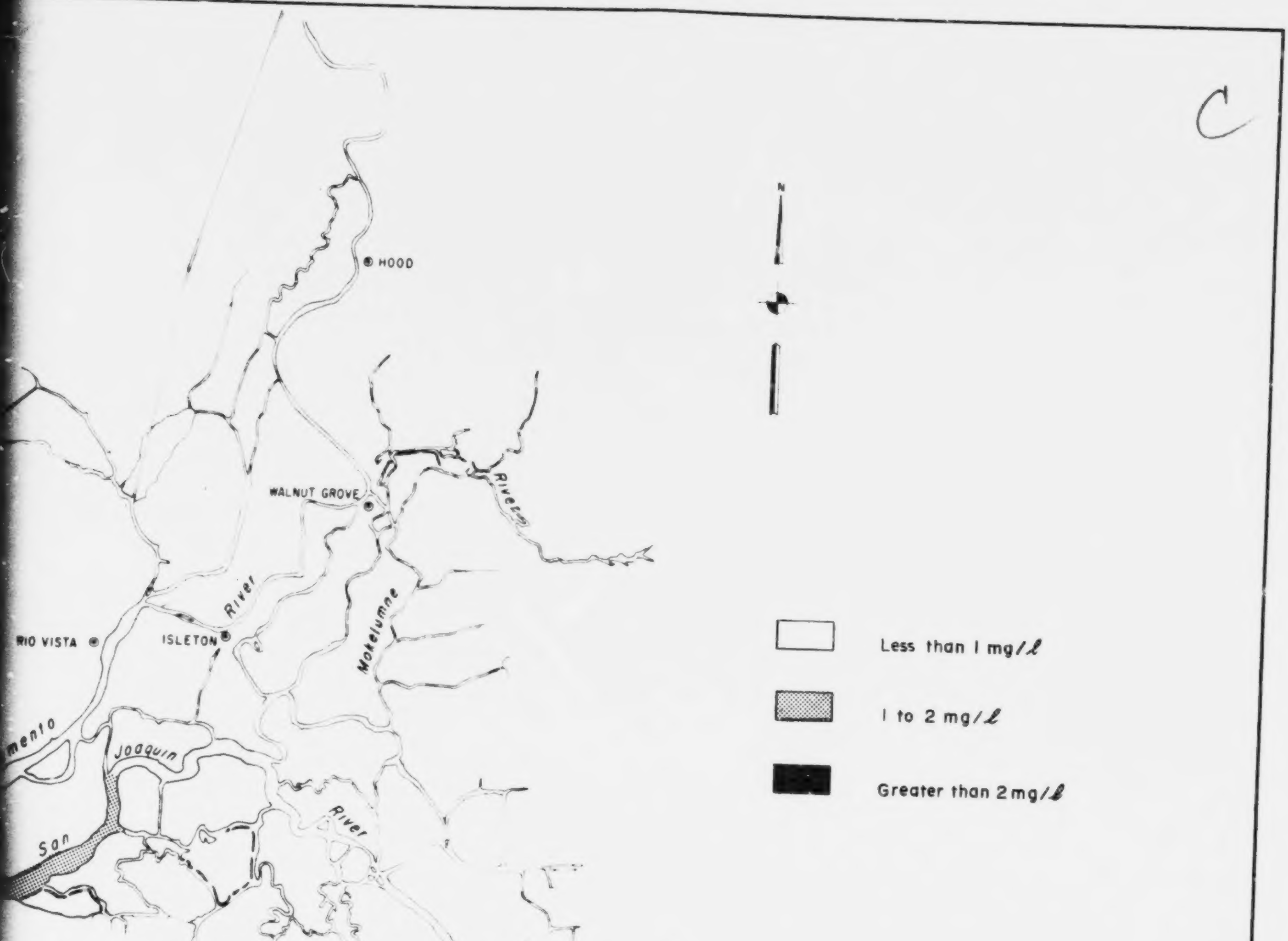
CENTRAL PACIFIC

MEAN
TOTAL NITROGEN
SUMME

U.S. DEPARTME
FEDERAL WATER POLLUT
SOUTHWEST REGION

16-A

C


N
HOOD
WALNUT GROVE
River
Mokelumne
River
RIO VISTA
ISLETON
mento
Joaquin
River
San
CONTRA COSTA CANAL
Calaveras River
STOCKTON
San
Joaquin
River
Middle
Old
River
River
TRACY PUMPING PLANT
TRACY
Less than 1 mg/ℓ
1 to 2 mg/ℓ
Greater than 2 mg/ℓ
SCALE IN MILES
2 1 0 2 4 6 8 10

CENTRAL PACIFIC BASINS PROJECT

MEAN OBSERVED
TOTAL NITROGEN CONCENTRATION
SUMMER, PRESENT

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMINISTRATION
SOUTHWEST REGION SAN FRANCISCO, CALIFORNIA

16-A

FIGURE 5

Antioch Bridge during the mid-June - mid-July period in 1961 yielded a median NO_3N (all tides and all depths sampled) concentration of 0.02 mg/l (ammonia test used in 1961 was not sensitive below 1 mg/l) and in 1962 a median of 0.01 mg/l of NO_3N plus NH_3-N (3). No sampling was reported during June - July 1963. In 1964 nitrate-nitrogen concentrations at the Antioch Bridge reached a reported low of 0.02 mg/l on July 2, 1964, based on fortnightly sampling (4). FWPCA studies in 1966 indicated nitrate and ammonia-nitrogen exhaustion occurred in Grizzly and Honker Bays and in the waters around Port Chicago within the mid-June - mid-July period (6). Algal populations were highest at this time and were comparable with population (chlorophyll) levels found in laboratory incubation of Bay and Delta waters when nitrate-nitrogen exhaustion occurred. Figure 6 illustrates the changes in mean nitrate-nitrogen concentrations at the Antioch Bridge between 1960-1963 (3).

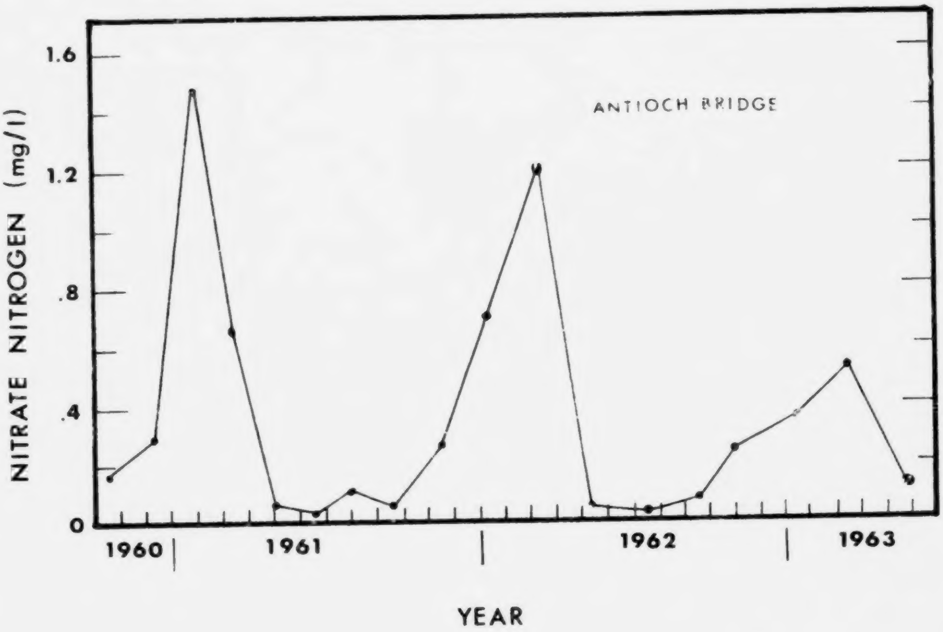
During the period May-October organic nitrogen forms are typically dominant and at times represent essentially all the nitrogen present in the water with the exception of dissolved nitrogen gas. Dissolved nitrogen gas is not an important nutrient source except to certain nitrogen-fixing species of bacteria and blue-green algal. Organic nitrogen forms occur as particulate matter such as algal cells, detritus, zooplankton and bacteria and soluble forms representing biotic excretions, decomposition products and soluble organic wastes discharged from the urban complex.

In conclusion, based on available data, the nitrogen available as a plant nutrient in Suisun Bay and western Delta waters appears to be effectively converted to organic forms during the late spring - early summer at the present level of enrichment.

Phosphorus. Total phosphorus (P) concentrations in the Bay-Delta system are relatively uniform and typically range from 0.10 - 0.30 mg/l as P of which usually less than one-half is present as dissolved orthophosphate-phosphorus at any given time. (3)

Phosphorus recycles into water from suspended and bottom sediments. Pomeroy (1965) reports on his work in Georgia that release of phosphate from sediments can support continued growth of phytoplankton bloom, even though there is only enough phosphate in the water to support the observed rate of photosynthesis for one day (7). Blooms in tidal creeks have maintained high rates of photosynthesis for weeks supported only by phosphates from the sediments where turbulence is significant.

Phosphorus contributions from sewage (predominantly from detergents), the recycling phenomenon and the presence of a super-abundance of phosphate in the water during times of inorganic nitrogen exhaustion lead to the conclusion that phosphorus is not a limiting plant nutrient in San Francisco Bay waters. Also, phosphorus is not likely to become a limiting nutrient unless significant changes are accomplished in the local waste treatment practices, detergent buffers and suspended sediment carrying capacity.



Data collected by
University of California
San Francisco Bay Study

CENTRAL PACIFIC BASINS PROJECT

NITRATE—NITROGEN VARIATIONS

DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMINISTRATION
SOUTHWEST REGION SAN FRANCISCO, CALIFORNIA

FIGURE 6

Minor Nutrients

Trace Elements. Nutrients also include various elements which may be necessary to plant growth but only in required trace amounts. Chief among these minor elements are the following: Potassium, Magnesium, Sulfur, Calcium. Others include Iron, Manganese, Copper, Molybdenum, Zinc, Cobalt, Sodium, Vanadium and possibly Chlorine. Many of these are present in sea water; probably all are included among the various waste discharges to the Bay and tributaries.

Vitamins. Among the minor nutrients considered important in the productivity of aquatic communities are the vitamins Vitamin B_{12}, Thiamine, and Biotin. Much remains to be learned regarding the importance of these to the growth of San Francisco Bay phytoplankton. The presence of Vitamin B_{12} and Thiamine is required for the growth of many of the pigmented flagellates. Vitamin B_{12} is reported to be required for some diatoms, including Skeletonema costatum, one of the dominant species in Suisun Bay (8). Biotin is less frequently listed but is a requirement for some dinoflagellates and yellow brown flagellates.

The California Department of Public Health has established the presence of vitamin B_{12} in the Sacramento River and has reported a progressive increase in B_{12} downstream resulting from waste discharges (9). These data indicate there is probably a considerable amount of B_{12} discharged to Suisun Bay via the western Delta and from treatment plants located along the Bay shore.

On the basis of available data and with continued discharges of treated sewage effluents and land runoff to the Bay-Delta system ample amounts of vitamins are expected in these waters.

Dissolved Silica. Dissolved silica (SiO_2) is present in natural waters largely as a result of land drainage. Concentrations in the Bay waters vary with season, the highest (20 mg/l), occurring in eastern Suisun Bay during high runoff periods (3). During the spring-summer of 1964 dissolved silica in San Francisco Bay ranged from nearly 15 mg/l to less than 1 mg/l (4). Oceanic values 5-15 miles off the Golden Gate were generally less than 3 mg/l (4).

Diatom frustules (shells) are composed of silica. Seasonal variations in dissolved silica resulting from diatom growth have been observed in the English Channel and in Narragansett Bay. Dissolved silica has been reported as limiting to diatom growth in the English Lake District at concentrations below .5 mg/l.

In conclusion, reductions in fresh water outflow from the Delta may lead to seasonal exhaustion of dissolved SiO_2 from Suisun Bay waters.

ALGAL POPULATIONS

Bay-Delta algae include microscopic (free floating) phytoplankton and both microscopic and macroscopic benthic (bottom-dwelling) plants on shallow tidal flats.

Phytoplankton Populations

Phytoplankton identification and counts, primary production and pigment measurements have been assembled from data gathered from several studies of the Bay. A general pattern for the Bay was developed from University of California phytoplankton counts and identifications. These data, which were gathered at intervals of about 2 months were supplemented with data gathered at 13 Stations every two weeks between May and September 1964, by the FWPCA (then DWS&PC, PHS) and the University of California (4). From these data the North Bay System was characterized as to phytoplankton character and relative abundance by geographical areas.

The dominant flora during these and other more recent studies were almost always centric diatoms including the genera Skeletonema, Thallasiosira, Coscinodiscus, Melosira and Cyclotella. Usually the next most prominant group were the Pennate diatoms Nitzschia, Navicula and Pluerosigma. Planktonic green and blue-green algae were sometimes found, usually in the upstream areas of the Bay and Delta. Various members of Cryptomonad group were apparent at times, particularly Rhodomonas and Crysococcus. Dinoflagellates were found in the more marine areas of the Bay, usually in low numbers; Ceratium and Peridinium were the most common genera.

The spring-summer of 1966 produced a large population of a marine cilliate-possibly Mesodinium rubra which caused dark red discolorations in large areas of San Francisco Bay (10). Nitrate-nitrogen was depleted in surface samples collected from discolored patches near Crockett in Carquinez Straits during the spring. Nitrate-nitrogen was greater than 0.25 mg/l at Crockett throughout the summer of 1964 (4).

Lackey (1966) reports he has never seen the blue-green alga, Microcystis, nor a great abundance of Anabaena, Oscillatoria rubescens or Gleotrichia (common blue-green nuisance forms) in salt or brackish waters (11). There are few marine planktonic blue-greens, a notable exception is Skejaella of the Red Sea. Lackey expects that with increased nutrients and clarity that there would be more diatoms, dinoflagellates, cryptophaceae, green euglenids and tintinnid ciliatea.

Increased diatom populations are likely under conditions of greater enrichment, however, the effect of decreased fresh water outflow may lead to exhaustion of dissolved silica in some areas of the estuary. Skeletonema, a diatom containing little SiO_2, is the most common genera found in Suisun Bay during summer periods when dissolved SiO_2 levels are low. Should silica become limited in enriched, otherwise productive areas, the dominant algal genera may change. It should be noted that certain planktonic green algae such as Nannochloris have thrived in brackish waters of Great South Bay (12). The dominant alga in several large tanks containing Bay water of nearly pure sea water salinity incubated during August 1966 at SERL was a green flagellate Platymonas. Green flagellates including euglenoid types were common in the enriched, brackish Petaluma and Napa River estuaries in the summer of 1966 (6). Dinoflagellates are common in estuaries as are some of the Cryptomonads. None of these forms require silica.

Geographical distributions of the North Bay system as found in the spring-summer of 1964 indicate that Suisun Bay generally supports the highest phytoplankton crop. Standing crop and photosynthetic activity using carbon-14 tracer techniques were highest in the Suisun Bay and western Delta stations (4). Crop levels and activity were lower in San Pablo Bay and western Delta stations upstream, see Figure 7.

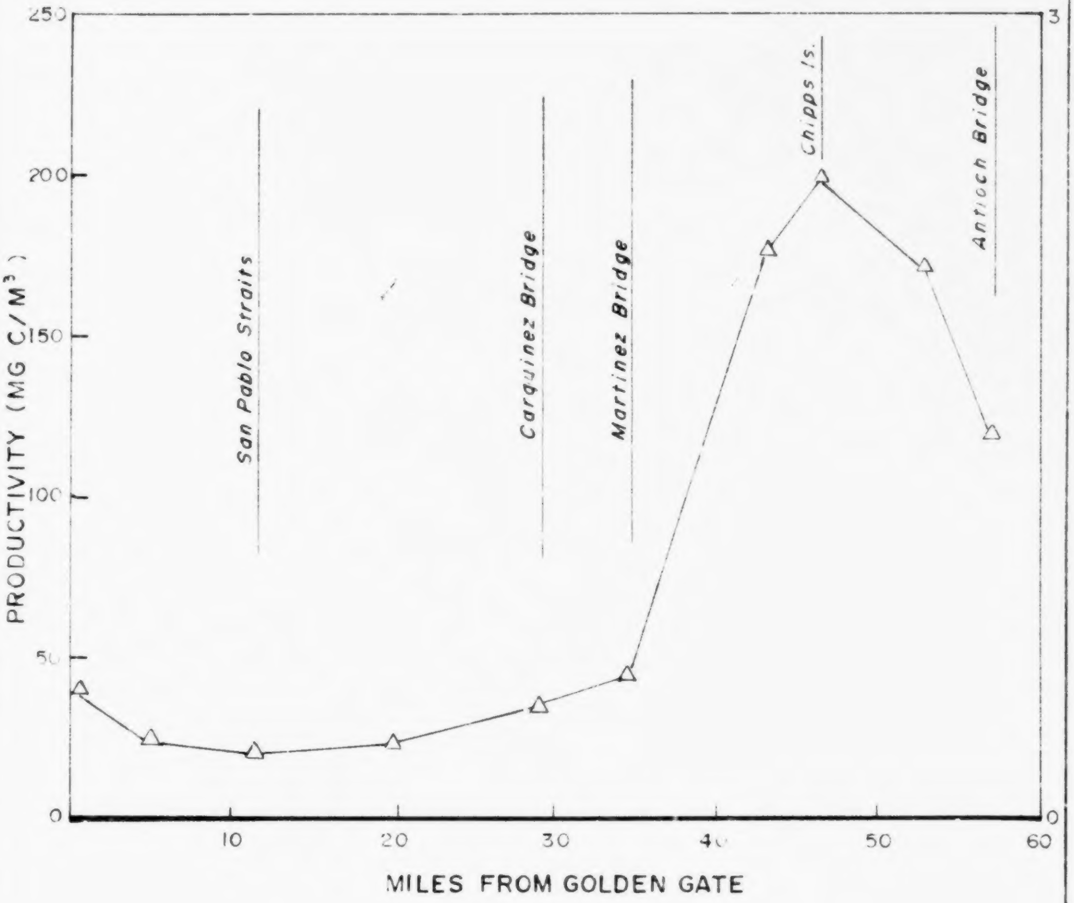
Chlorophyll techniques have been employed by the FWPCA and by the California Department of Fish and Game in their more recent studies in the Bay-Delta region. Both groups have also carried out phytoplankton cell counts including biomass measurements to supplement pigment data.

Chlorophyll levels in the Suisun Bay and western Delta areas were measured during the spring, summer and autumn of 1966. Figure 8 depicts chlorophyll levels in the Antioch Bridge area (within the 30 foot deep, dredged ship channel) and Figure 9 combines data from the shallower areas of Grizzly and Honker Bays. These data were furnished by the California Department of Fish and Game, Delta Studies, Stockton, California. The mean summer chlorophyll level measured in Grizzly and Honker Bays was about 35 µg/l compared with about 20 µg/l at the Antioch Bridge. Peak values exceeded 100 µg/l in Grizzly Bay and 35 µg/l at the Antioch Bridge.

Tide Flat Algae

During the period of October 1965 through the summer of 1966, FWPCA personnel routinely observed the changes in the ecology of a tide flat near Albany in San Francisco Bay. The area of concern serves as a local example of eutrophication surpassing nuisance levels.

In October 1965 the presence of green seaweeds Ulva and Enteromorpha was established. These plants were found as fragments floating or stranded in the shallows. Sediment samples were analyzed using microscopic techniques and were found to contain the pennate diatoms of the genera Navicula and Nitzschia.



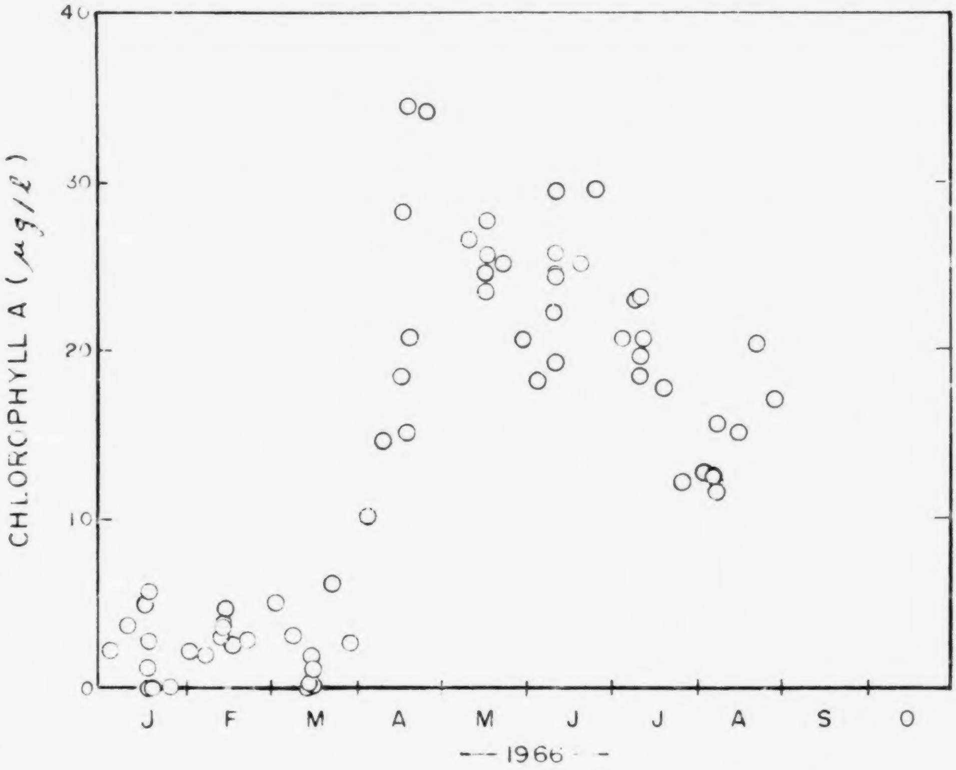
CENTRAL PACIFIC BASINS PROJECT

MEAN PHYTOPLANKTON PRODUCTIVITY
SAN FRANCISCO BAY
MAY– AUGUST, 1964

DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMINISTRATION
SOUTHWEST REGION SAN FRANCISCO, CALIFORNIA

20-A

FIGURE 7



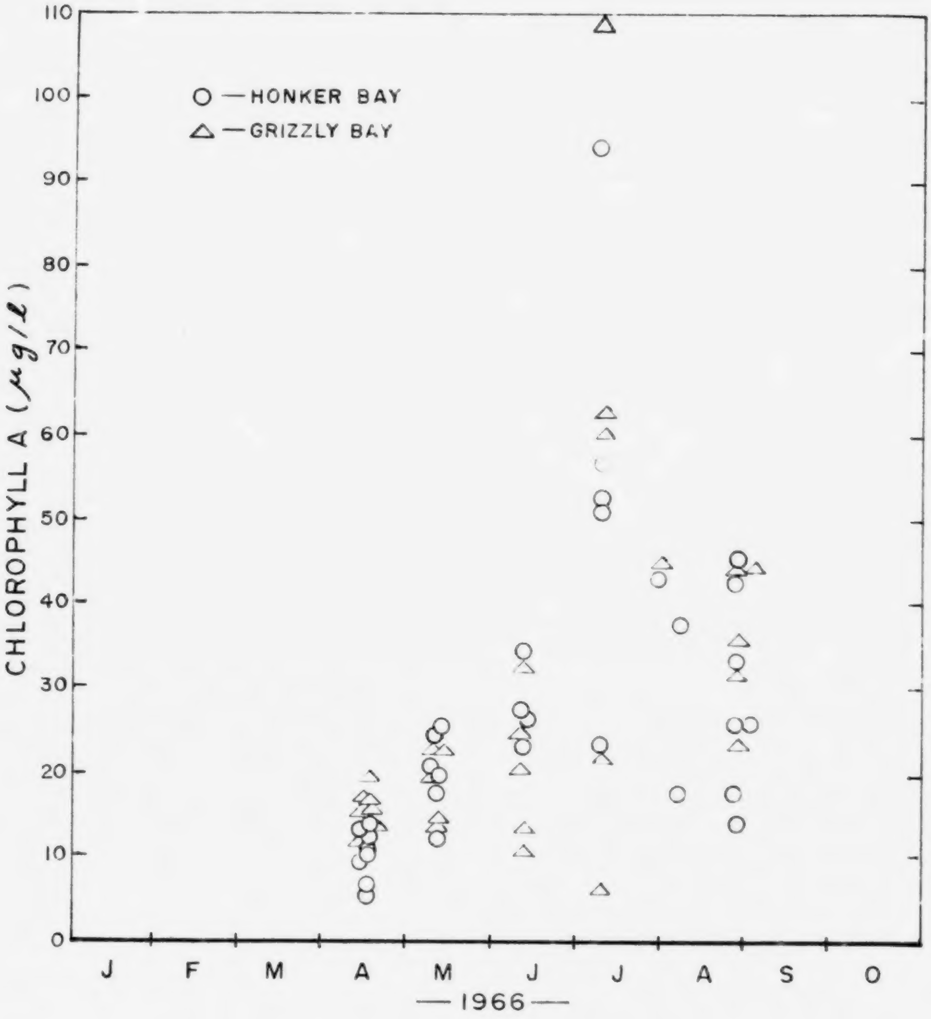
NOTE: Chlorophyll data furnished by California Fish and Game, Delta Fish and Wildlife Protection Study.

CENTRAL PACIFIC BASINS PROJECT

CHLOROPHYLL VARIATIONS
ANTIOCH BRIDGE

DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMINISTRATION
SOUTHWEST REGION SAN FRANCISCO, CALIFORNIA

FIGURE 8



NOTE: Chlorophyll data furnished by California Fish and Game, Delta Fish and Wildlife Protection Study.

CENTRAL PACIFIC BASINS PROJECT

CHLOROPHYLL VARIATIONS
GRIZZLY & HONKER BAYS

DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMINISTRATION
SOUTHWEST REGION SAN FRANCISCO, CALIFORNIA

20-C

FIGURE 9

During the winter period no green seaweeds were present and dominant flora were the pennate diatoms. The populations were measured in April and were considered low as compared with other areas, especially those with more stable substrates. The silty flat is churned up by tides and the prevailing west winds.

During the spring and summer, observations were made of green seaweeds on the flat, including Chaetomorpha, Ulva, and Enteromorpha, and the buildup of stranded algal scums made up of Ulva and Enteromorpha. Chaetomorpha populations created a dark green mat over much of the flat which was nearest the shore. The density of the Chaetomorpha populations was 1-2 lbs. per square meter. Ulva and Enteromorpha buildups in the denser areas were 3-4 lbs. per square meter in early June and reached peaks of 31 lbs. per square meter by June 15, and 80 lbs. per square meter by July 5.

On hot days between June 15 and July 10 the flat yielded an objectionable odor characteristic of H_2S. Inspection of the stranded vegetation clearly confirmed that decomposition of these seaweed was responsible for the odors. The sulfur content of Ulva is known to be about 4 percent of the dry weight (equal to or greater than the nitrogen content). The presence of the fertilizing influences of nitrogen and phosphorus from a nearby sewage treatment plant and the configuration of the tidal basin create a nutrient trap suitable for prolific growth of green seaweeds.

Other areas have experienced nuisance conditions of tide flats created by large populations of green seaweeds. Letts and Adeney described nuisance problems created by 2-3 ft. thick mats of Ulva latissima and Enteromorpha sp. in the upper reaches of Belfast Lough (13). Sewage contamination was related to the problem. Wilkinson described the progressive buildup of green seaweed in the nitrogen-rich estuary of the Heathcote and Avon Rivers and the associated H_2S generation causing nuisance odors and blackening of lead-based house paints (14). Ulva and Enteromorpha mats attached to mud or mollusk shells were considered dense if in excess of 10 lbs. per square meter. Sawyer described the Sea Lettuce (Ulva) problem in Boston Harbor which included nuisance odors in a sewage contaminated area. Large protected mud flats were abundant with Ulva (15). Elser has described similar problems in the tidewater Maryland area (16).

In addition to the observations at the Albany tide flat, other tide flat field studies were conducted at Sausalito, Crockett and Dillon Point in the Bay System and at Bolinas Lagoon and Bodega Bay on the outer coast. Green seaweeds were observed at all locations but were scarce at the less saline areas at Crockett and Dillon Point even where firm substrate was available. At Sausalito Enteromorpha creates a green entanglement in the near shore, but this was present only in the spring and not considered of nuisance proportions. At Bolinas and Bodega Bays Enteromorpha mats were observed stranded along the shoreline at numerous places near homes and docks during the summer of 1966. The mats at Bodega were considered of nuisance proportions and are believed to be increasing with the increased volume of raw and partially treated sewage which reaches the Bay. Bodega Bay is less turbid and more protected than most of the shallow water areas of San Francisco Bay.

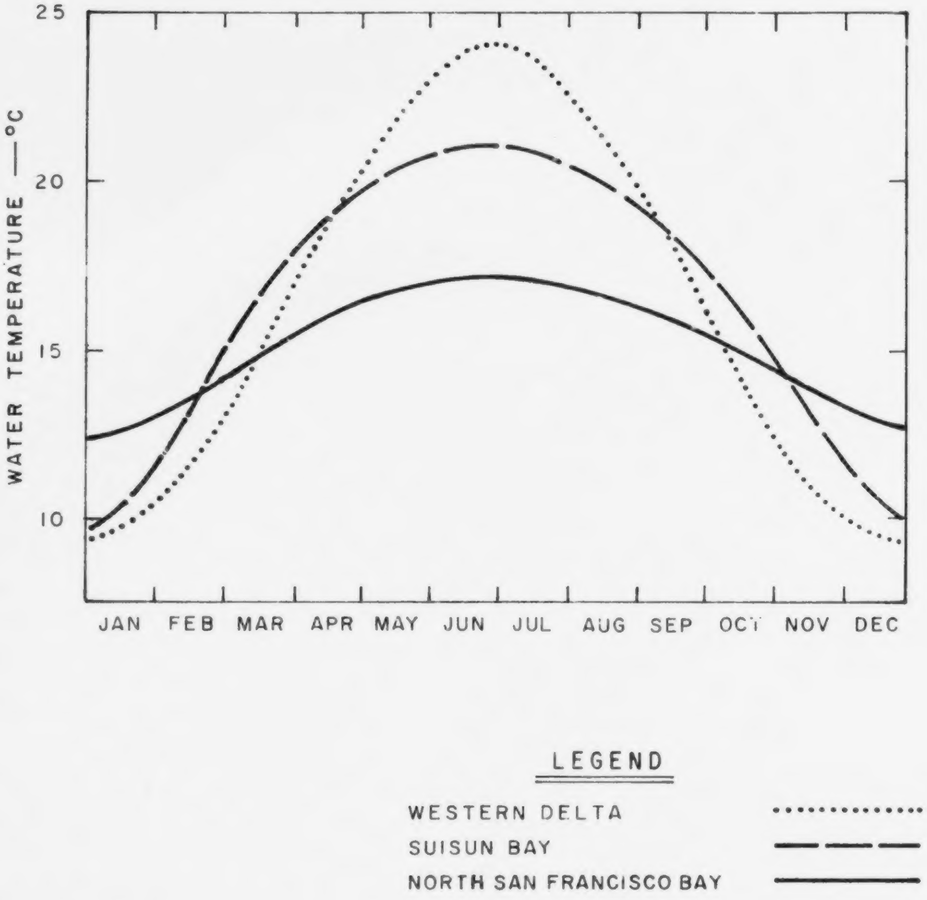
Diatoms are the most common flora of the flats. Many of them can penetrate the interstices of the silt or form sheaths and mucilaginous coatings and thus maintain themselves through tidal disturbances. The flats retain considerable moisture after the ebb tides and the diatoms can carry on photosynthetic activity under high light conditions. The most dominant forms are those that are able to move through the silt and detritus. These are primarily pennate diatoms. Diatoms are common to estuarine mud flats throughout the world and present no particular problem.

TEMPERATURE

Seasonal increases in water temperature serve to stimulate primary production during the spring and summer in the Bay and Delta. Figure 10 illustrates the seasonal water temperature variations in the Western Delta, Suisun Bay and North San Francisco Bay. The temperature ranges within the estuary are generally cool as compared with many other estuaries in temperate climates. For example, water temperatures in Chesapeake Bay exceed 25°C in areas of greater than one-half sea water salinity; in San Francisco Bay water temperatures seldom exceed 20°C except in Suisun Bay and upstream. The cooler character of these waters is a factor in the ability of this estuary to support salmonid fishes.

Fresh water flows into and through the Delta will be significantly decreased in future years due to the operation of the Peripheral Canal. While this could bring about a slight increase in summer water temperatures in the north-eastern Delta and slight decreases at points where water is released from the Peripheral Canal, these changes are not considered to be significant to overall water temperature conditions in the Delta. In evaluating future water quality conditions, therefore, it has been assumed that existing Delta water temperatures would prevail in the future.

Water temperature levels encountered or expected in the San Francisco Bay and Delta system in spring and summer are not considered limiting to algal growth.



CENTRAL PACIFIC BASIN PROJECT

WATER TEMPERATURE VARIATIONS
SAN FRANCISCO BAY ESTUARY

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMINISTRATION
SOUTHWEST REGION SAN FRANCISCO, CALIFORNIA

21-A

FIGURE 10

SUSPENDED SEDIMENTS AND LIGHT PENETRATION

Light energy is essential to photosynthetic production. Therefore, suspended inorganic and organic sediments and their effect on light penetration must be considered before the effect of nutrient additions can be assessed. Projections of inorganic sediment concentrations are based on sediment load projections contained in a report by Dr. R. Krone to the Federal Water Pollution Control Administration (17). Predicted light penetrations are based on the Beer-Lambert Law using the sediment projections.

Suspended Sediments

The suspended solids vary from place to place and time to time in the estuary depending largely on outflow, the proximity of shallow areas, currents, flocculation and algal populations. Table 4 contains suspended solids data from various locations in the estuary.

TABLE 4

SUSPENDED SOLIDS CONCENTRATIONS -
SAN FRANCISCO BAY ESTUARY
(HL WATER SLACK 1961-1963)(a)

Location (b)	Median	Range
Antioch	38.5	29-65
Collinsville	54.5	38-81
Middle Point	58.5	19-106
Martinez Bridge	54.5	9-163
Carquinez Bridge (Crockett)	38.0	11-180
San Pablo Bay	42.5	-128
Point San Pablo	15.5	6-65
Golden Gate Bridge	8.0	5-14

(a) University of California Bay Studies.(3)

(b) For locations see foldout map in back of report.

The average suspended solids concentration for Suisun Bay and the western Delta stations in July 1962 was 57 mg/l and in September 1962 was 50 mg/l. By late October after some rains the average level was 72 mg/l(1). A level of 50 mg/l appears to be a reasonable average figure for the area during the dry season.

Light Penetration

Light penetration varies greatly through the Bay-Delta System. Transparency measurements using Secchi discs and photometers have been made by the University of California, the California Department of Fish and Game and FWPCA. Transparency measured by Secchi disc depth varies from 2-3 meters at the Golden Gate to less than 1/3 meter in Suisun Bay and much of the Delta.

The Beer-Lambert Law describes light penetration in water as a function of the concentration and character of suspended material.

$$I = I_o e^{-kdc}$$

where
I = light intensity at depth d (d in meters).
I_o = light intensity at surface.
k = coefficient related to character of suspended material.
c = concentration of suspended matter.

Sometimes the Beer-Lambert Law is stated as $I = i_o e^{-kd}$ where k is an extinction coefficient which defines the rate at which light penetration changes through the water column.

The depth at which the light intensity is equal to 1% of the surface light is often considered the extent of the water column where photosynthesis is important. This layer of water is defined as the euphotic zone (d') and can be expressed in terms of k by:

$$d' = \frac{4.6}{k}$$ where d' is in meters

Extinction coefficients vary from about 0.5 at the Golden Gate to more than 5 in Suisun Bay and the Delta. An extinction coefficient of 5 is equivalent to a euphotic depth of 0.92 meters or about 3 feet.

Secchi disc measurements have been related to extinction coefficients by the expression:

$$d_s = \frac{1.7}{k}$$ where d_s is the Secchi disc depth in meters.

The Secchi disc depth relates to light intensity equal to 18.2% of the surface illumination on this basis. The differential extinction of various energy levels or wavelengths of light are not considered in this brief treatment of the light extinction question. A detailed account of the differential extinction of light is presented in Plankton and Productivity of the Oceans by Raymont (18) and in The Oceans by Sverdrup et al (19).

Suspended sediments in Suisun Bay and the Delta are varied; they include inorganic silts and clays brought in by the rivers and resuspended by currents and organic material of several origins. The organic material includes the living plankton as well as detrital material. A unit weight of suspended organic material has a greater effect on the extinction coefficient than a similar weight of suspended inorganic material. According to Postma, the relative effect of light extinction by suspended organic material may be 12 to 52 times that of inorganic sediments although the semitransparency of algal cells may tend to lower the factor somewhat (20). Also, a greater reduction in light penetration will result in a unit weight of clay sized particles as compared with a unit weight of sand. The presence of suspended organics tends to increase the value of the sediment character coefficient (k) of the Beer-Lambert Law.

The highest suspended solids concentrations are usually found in the transition zone between fresh and salt waters. This is in part due to a chemical flocculation effect brought on by the initial mixing of the fresh and ocean waters and by increased plankton production. The transition zone of many estuaries is more productive than the areas upstream or downstream due in part to the presence of various nutrients brought together by the land drainage and ocean waters. Suisun Bay encompasses the transition zone in the San Francisco Bay system.

Projections

Three factors, all man-caused, serve as a basis for predictions in a changed sediment regimen. The factors include (1) lower volume of sediment transport due to rerouting of flow-bearing sediments around the Delta, (2) lessened effect of resuspension by wind and tide due to stabilization sediments under sustained low flow conditions, (3) trends toward physically removing dredge spoils from the estuary.

Changes in the fresh water inflow to the Delta will effect changes in the concentrations of suspended sediment materials (principally clays and silts) found in the Delta channels and in the San Francisco Bay. The first two factors are directly related to the changes in fresh water inflow to the system.

Dr. R. Krone in his report on San Francisco Bay sediments discusses the changes in sediment inflow in some detail. His projections for future sediment tonages are based largely on the changes in hydrology as projected by the U.S. Bureau of Reclamation, on past sediment transport work carried out by the U.S. Geological Survey (USGS) and the U.S. Army Corps of Engineers (USACE), and on his work with Dr. Einstein at the University of California, Berkeley.

The Krone report estimates that a median value of 2.6 million tons annually are transported from the Delta to the Bay under present (1960) conditions. Future sediment transport predictions are predicated on outflow information furnished by the U. S. Bureau of Reclamation (USBR)and the assumption that future hydrologic conditions regarding rainfall and runoff are comparable with the past records. The median annual sediment transport prediction for 1990 conditions as estimated by Krone is 0.7 million tons and for 2020 conditions 0.4 million tons.

Wind and tidal currents are expected to have a lesser effect under future controlled outflow conditions. Sorting of fines deposited in shallow areas is expected to lead to a more stable bottom. Much of what is resuspended will deposit in deeper areas where resuspension is unlikely. The bathymetry of the Bay is continually altered by sediment material that is deposited in the shallows. Thus the combined effect of reduced outflow and reduced sediment transport tends to accelerate the clearing of the Bay waters.

Dredging operations tend to disrupt the natural sedimentation process since more stable sediments in deeper areas are disturbed. Any trends to remove sediments dredged from the ship channels to either the ocean or the land will also tend to improve Bay water transparency. There is considerable interest in removal of dredge spoils from the Bay. The San Francisco Bay Conservation and Development Commission (BCDC) has reported that contractors for the Bay Area Rapid Transit District are considering taking dredged materials from its San Francisco - Oakland tube out beyond the Golden Gate (21).

The dredge spoils from the U. S. Army Corps of Engineers channel improvements between San Francisco and Stockton call for both land (71%) and ocean (11%) disposal.

The BCDC cites that the disposal of dredge spoils at sea is the most effective method but has not been practiced in the Bay area to any great extent, the high cost involved and lack of equipment being the reasons.

Reduction in Delta outflow to approximately 1500 cubic feet per second for long periods of time are specified by the USBR operations data. The effect on sediment concentrations is expected to follow these hydraulic changes. Dr. Krone, in his report to the FWPCA, has computed his projected annual sediment tonages on the basis of the USBR hydrology and on empirical relationships between river flow and sediment concentration. Based on the flow changes and the bottom sediment stabilization tendencies described earlier the predicted suspended sediment concentrations are assumed to be in direct proportion to sediment inflow. Therefore, if an average suspended solids concentration of 50 mg/l is assumed for Suisun Bay the projected 1990 concentration becomes 14 mg/l and 2020 concentration becomes 8 mg/l. These projections do not include effects of organic matter or the flocculating effect of the seawater-freshwater interface in certain chloride zones.

Sustained low Delta outflow will probably lead to greater incursion of oceanic salts which will move the zone of flocculation upstream.

Changes in water transparency due to suspended inorganic sediment reductions will permit light energy to penetrate deeper into Bay waters. Increased productivity involving greater phytoplankton crops will tend to increase turbidity. The productive system tends to reach a more turbid state on seasonal cycles, but the turbidity is then more a result of suspended organic matter than silt.

Light penetration estimates presented in Table 4 are based on predicted inorganic suspended sediments and the use of the Beer-Lambert Law. The tabulated values for depth of the euphotic zone represent the depth at which surface light is reduced to 1% of its incident value. The euphotic zone defines the volume of water where photosynthesis can take place.

TABLE 5

SEDIMENTS AND LIGHT PENETRATION - PROJECTIONS

Year	Median Annual Sediment Transport (10^6 Tons)	Suspended Sediment mg/l		Depth of Euphotic Zone (ft)	
		San Francisco Bay	Suisun Bay	San Francisco Bay	Suisun Bay
1960	2.6	10	50	14	3
1990	0.7	3	14	50	10
2020	0.4	2	8	70	20

Future increases in water transparency due to reduction of suspended inorganic sediments will permit light energy to penetrate much deeper into Bay waters than at present. This enlargement of the euphotic zone will, in turn, permit the growth of greater algal populations which themselves create turbidity. The overall net effect of this growth on water transparency will depend on the nutrient level, water temperature, and other factors related to growth of algae.

LIMITING FACTORS

Environmental conditions in Suisun Bay-western Delta waters are limiting to algal growth in several ways. During winter sediment-caused turbidity is high and water temperature and solar radiation are low and algal populations are also low. During spring as these waters warm up, available light energy increases and sediment loads drop, the available nutrients are converted to algal cells (including planktonic and attached forms). Inorganic nitrogen (nitrate, nitrite and ammonia) concentrations fall as the algal crops increase and reach starvation levels in Suisun Bay usually in June or July. Inorganic phosphorus levels are not generally reduced to starvation levels considering the reservoir of these forms found on Bay-Delta sediments.

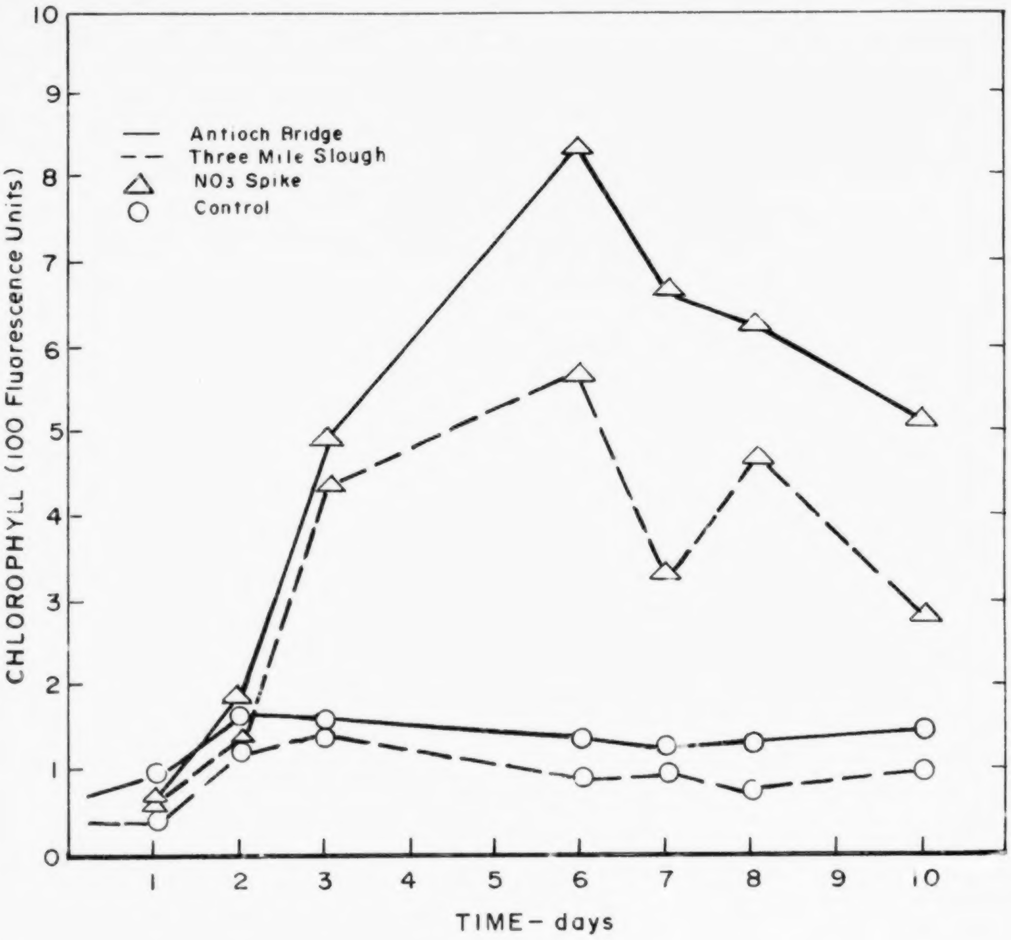
Experiments involving light incubation of Bay waters containing native Bay planktonic algae were performed under contract arrangements at the University of California (SERL) in 1966 (6). These experiments demonstrate the general deficiency of inorganic nitrogen in Suisun Bay and Western Delta waters as compared with other nutrients. In summary, these experiments included six replicated laboratory scale flask studies where nutrient sources (including C, N, P, SiO_2) were added to Bay waters (various parts of the Bay were assessed separately). In all experiments the nitrogen-spiked flasks yielded higher algal crops (cell counts or chlorophyll levels) than controls or in phosphorus-spiked flasks.

Six additional experiments were carried out on a larger scale where Delta and Bay water samples were incubated in the field in larger chambers. Typical Bay diatom genera (dominant genus was generally Skeletonema) developed greater populations when inorganic nitrogen (usually NO_3-N) was added as compared with controls and phosphorus spikes. These experiments (carried out in the summer of 1966) were performed on waters sampled from Carquinez Straits on the west to Three Mile Slough and the Antioch Bridge on the east. Tile drainage and sewage spikes were also employed with resulting increases in algal crop (chlorophyll) as compared with controls incubated at the same site. Figure 11 serves to illustrate the pattern of results from two of the six chamber studies.

In addition to frequent measurement of chlorophyll, nitrate-nitrogen changes were also assessed. Nitrate-nitrogen exhaustion coincided with maximum chlorophyll levels. See Figure 12 for example. After nitrate exhaustion occurred, algal chloroplasts generally were pale and shifts in algal genera occurred. Samples held for a month or more yielded a sequence of algal dominance leading from diatoms to green algae in most cases.

The maximum chlorophyll levels (30-60 µg/l) achieved in the control flasks and chambers are comparable to the peak chlorophyll levels achieved in Suisun Bay and the western Delta during the June-July period when nitrate exhaustion has been repeatedly observed. In all cases nitrogen enrichment also resulted in increased algal growth rates as compared with controls incubated at the same temperature and light level.

Biological factors such as algal-grazing predators or inhibitory products may limit the algal population level or effective growth rate. Predator populations usually buildup after the algal crops have developed in the spring. These predators (zooplankton) ingest smaller algae and excrete soluble and particulate (detritus) organic materials which are decomposed by bacteria.



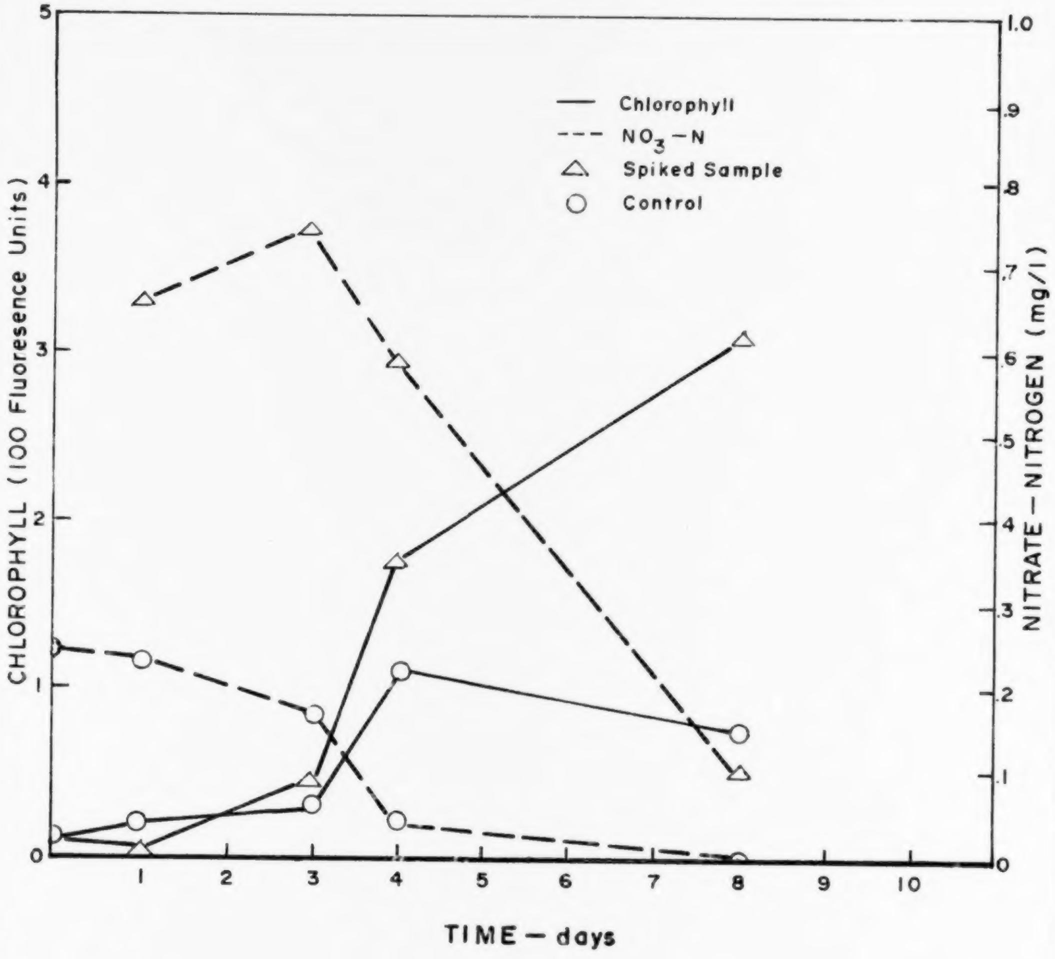
CENTRAL PACIFIC BASINS PROJECT

CHAMBER STUDIES
WESTERN DELTA

DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMINISTRATION
SOUTHWEST REGION SAN FRANCISCO, CALIFORNIA

28-A

FIGURE 11



CENTRAL PACIFIC BASINS PROJECT

CHAMBER STUDIES
CARQUINEZ STRAITS

DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMINISTRATION
SOUTHWEST REGION SAN FRANCISCO, CALIFORNIA

FIGURE 12

Inhibitory factors may include cell byproducts, wastes or other environmental factors which lower in situ growth potential. Refinery wastes and settling of flocculated sediments have been mentioned as possible inhibitory factors in the Bay. Interferences caused by silt (suspended) have been related to the clarity of the water, but salinity-induced flocculation of silt may also trap smaller algal cells and carry these cells out of the water as the flocculants settle. The bulk of the flocculants currently settle out in San Pablo Bay where phytoplankton populations are low all summer. Occasional blooms of larger motile forms such as the cilliate, Mesodinum, demonstrate that there can be high planktonic populations even in San Pablo Bay. Mesodinum blooms in 1966 depleted nitrate-nitrogen levels in western Carquinez Straits where usually a relatively high NO_3-N has been observed through the year (10).

Algae thrive seasonally in the Suisun Bay-western Delta region at present although inhibition may be suspected in other parts of the system (such as San Pablo Bay).

Some algae, such as the blue green types, are less tolerant to high salinities. Lackey reports that he knows of no instances of nuisance growths of blue-green algae in waters containing more than 500 mg/l chlorides (22). Data from the Potomac estuary indicate that blue-green algae are typically found in waters of lower chlorosity except for cells which may wash downstream (23). Most green algae appear to be found in waters fresher than 5000 mg/l chloride, however, there are exceptions such as the macroscopic green seaweeds (Ulva and related forms) and plankton forms such as Nannochloris.

In turbid, enriched areas of the Bay-Delta system such as the Napa River, Petaluma River, Coyote Creek and lower San Joaquin River extremely high algal populations (>100 µg/l Chlorophyll) are reached in areas high in nutrients. Figure 13 illustrates the chlorophyll and total nitrogen levels in two of these tributaries as found during surveys in the summer of 1966 (6). Temperatures in the enriched areas were comparable with summer Suisun Bay-western Delta temperatures.

San Francisco Bay-Delta waters are currently very turbid as compared with other Bays such as San Diego, Chesapeake and Raritan. The relatively shallow depth of most of Suisun Bay permits light to extend deep enough into these waters to yield a net production of algal cells. Deeper, turbid areas (such as dredged channels) are not able to support net production through the water column and algal cells which accumulate in these areas will not thrive.

Temperature and light penetration in these waters are sufficient to permit full conversion of inorganic nitrogen forms to organic forms (algae, bacteria, zooplankton predators and various soluble and detrital byproducts) during the late spring and summer months. Dissolved silica depletions related to freshwater flow reductions and uptake by diatoms may lead to a shift in the character of planktonic algae from diatoms to other forms.

Considering the field observations, the relative concentrations of nitrogen as compared with phosphorus in sewage effluents (about 3:1), the rapid recycling character of phosphorus from sediments and the results of algal growth assessment studies described above, it is concluded that nitrogen is the most probable limiting element important to algal nutrition in the waters of Suisun Bay and the Delta in the general vicinity of the proposed drain discharge.

V. NITROGEN—ALGAE MODEL

Nitrogen has been concluded to be the probable limiting element important to algal nutrition in the waters of Suisun Bay and the western Delta. Observations during the spring - summer period by several study groups including the University of California (Berkeley), California Departments of Fish and Game and Water Resources and the FWPCA (and its predecessor agency) have shown that planktonic algal populations (and primary production) in Suisun Bay and the western Delta are highest in late spring and summer, and correspondingly that inorganic nitrogen is low, and may be essentially exhausted at various times during these months.

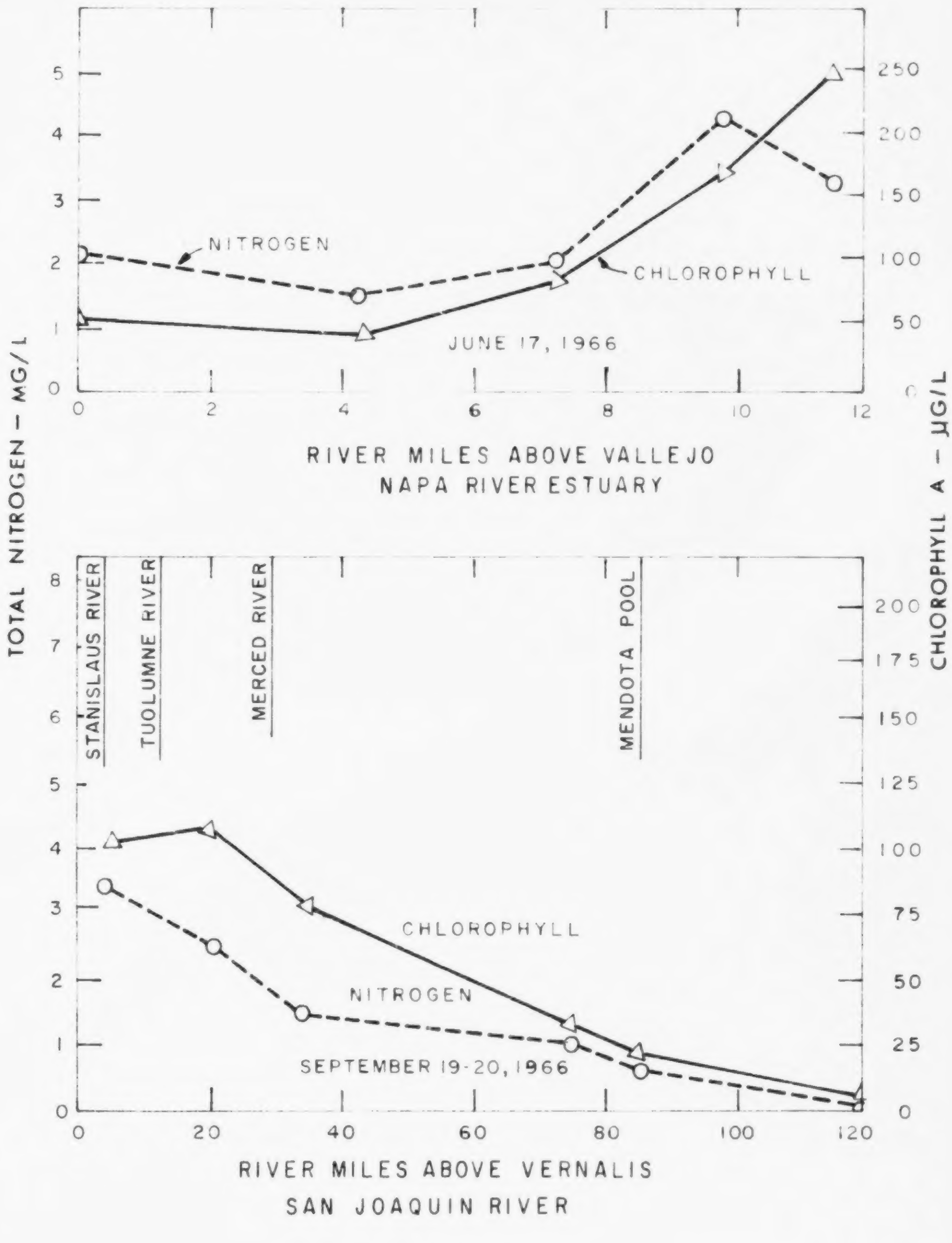
The data used here in developing relationships between algal crop and organic nitrogen in association with the planktonic algae are from recent State and FWPCA studies oriented to eutrophication aspects of water quality control and water resource management. Data used were from the San Francisco Bay and Delta (including various enriched tributaries) and the enriched Potomac and James River Estuaries on the East Coast.

Organic nitrogen-chlorophyll ratios have been determined from field and laboratory data. Data collected in the summer of 1966 by FWPCA from Suisun Bay and western Delta and in 1964 by USPHS demonstrate that organic nitrogen forms (particulate and soluble) account for most and sometimes essentially all of the total nitrogen present in these waters(6,3). Ratios of organic nitrogen-chlorophyll are plotted in Figure 14 from field data gathered in 1965-1966 from the San Francisco Bay estuary and enriched tributaries and from the nutrient-enriched Potomac estuary (23). Ratios ranged from about 5:1 to more than 50:1 from this field data. Most of the data is contained between the 10:1 and 50:1 ratios. Data from the James River estuary (24) were also inspected; however, these data did not include soluble organic nitrogen values and consequently the ratios were lower (typically 5:1 - 20:1).

A nitrogen-chlorophyll ratio of between 5:1 - 10:1 is considered representative of marine planktonic algae as separated from other organic matter. Under field conditions much of the organic material is detritus or soluble forms. For prediction purposes a range of organic nitrogen-chlorophyll ratios in Suisun Bay-western Delta region of 20:1 - 40:1 was used for the period May-October. At this time, essentially all of the nitrogen is assumed to be in an organic form, and assumption borne out by the available data.

Such predictions of algal crops accompanying differing degrees of nutrient enrichment are appropriate only when certain qualitative provisions are fulfilled. These include:

1. The waters in question (in situ) should already exhibit a nutrient limitation during some period of the year.



CENTRAL PACIFIC BASIN PROJECT

**NITROGEN AND CHLOROPHYLL
TRIBUTARY STREAMS**

U. S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMINISTRATION
SOUTHWEST REGION SAN FRANCISCO, CALIFORNIA

FIGURE 13

2. The *in situ* growth rates should be sufficiently high to permit projected algal crops to develop within the growing season.

3. Turbidity or light shading caused by the algal cells themselves should be included in the assessment.

4. The waters should be capable of growing higher populations of algae if the particular nutrient in question is added to these waters as demonstrated by laboratory experiments (i.e. to insure that a minor element or vitamin is not already limiting growth).

5. Predictions should be within a reasonable range of standing crop levels as observed in enriched natural waters of otherwise similar character.

The first condition (*in situ* nutrient limitation) has been described in preceding sections and it has been concluded that inorganic nitrogen is currently limiting algal growth in the late spring and early summer in Suisun Bay and western Delta.

The second condition can be considered by applying growth rate calculations to projected populations using the relationship $P_t = P_o e^{at}$ where:

P_t = Projected Population at time t

P_o = Initial population at time t = o

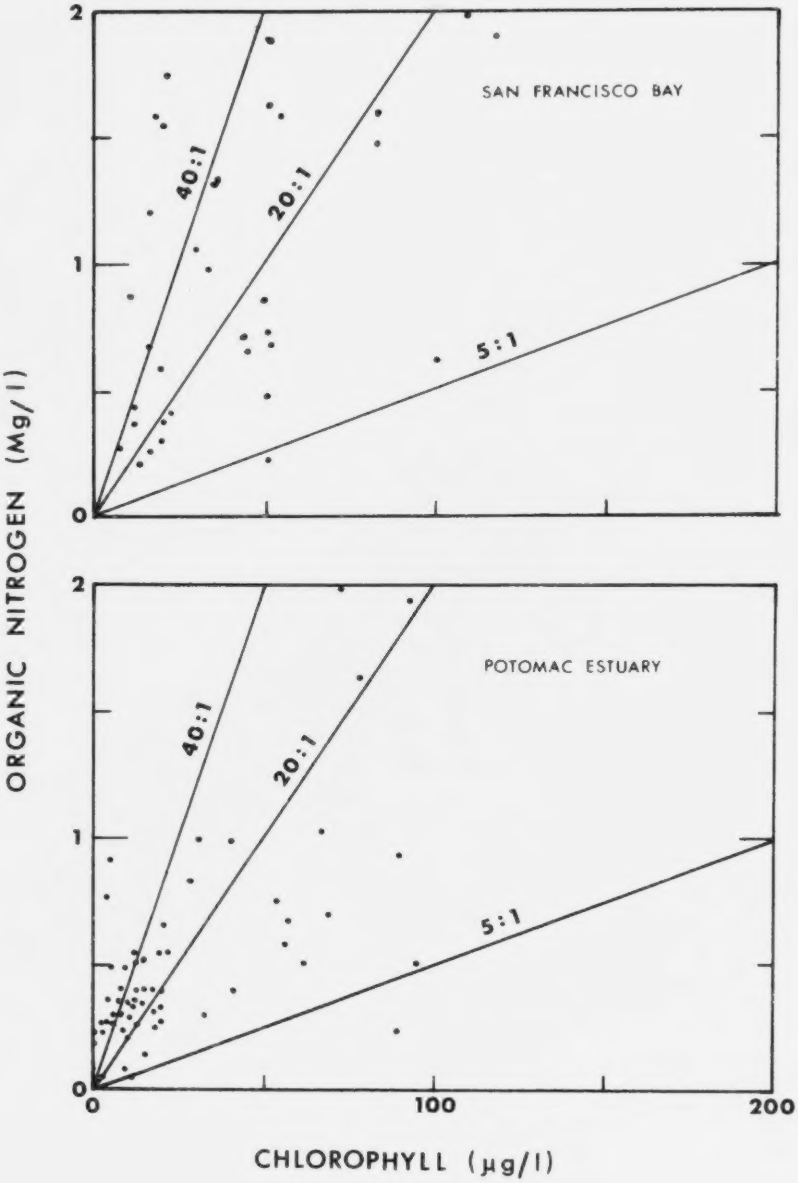
a = rate of change of standing crop (observed)

The crop rate constant "a" at the Antioch Bridge is estimated to 0.05 days^{-1} based on the observed time-chlorophyll sequence in 1966. See Figure 6.

Starting with Po = 5 µg/l in mid-March the required time to develop various predicted populations (P_t) under present turbid conditions would be:

P Chlorophyll (µg/l)	T Time (days)
10	13
25	32
50	46
100	60
200	74

Based on the above, the high projected populations (100-200 µg/l) can readily occur during the growth season. Even if the rate constant (a)



CENTRAL PACIFIC BASINS PROJECT

OBSERVED ORGANIC—NITROGEN AND CHLOROPHYLL CONCENTRATION

DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMINISTRATION
SOUTHWEST REGION SAN FRANCISCO, CALIFORNIA

FIGURE 14

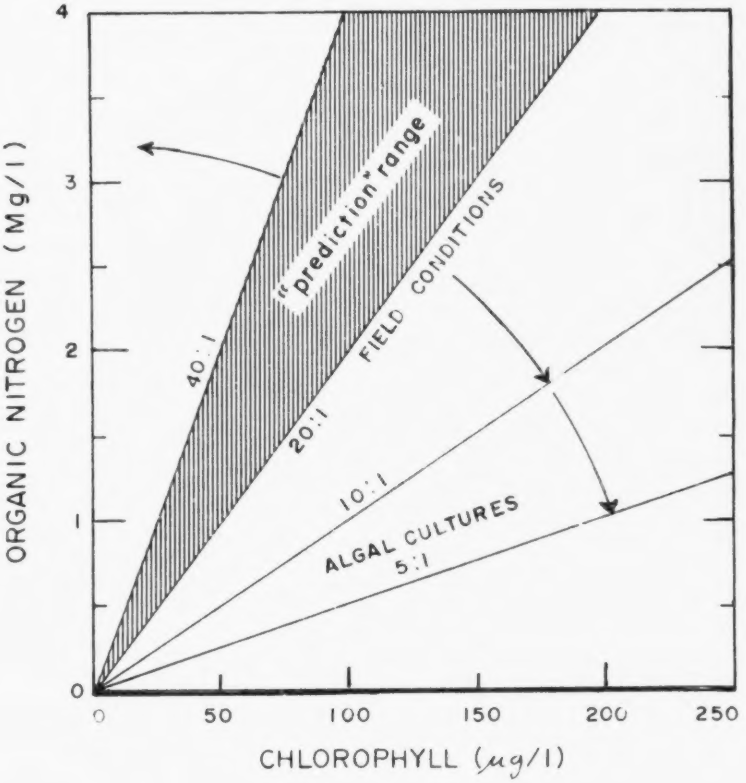
drops by 20% due to shading (condition 3), 200 μg/l population could still develop within 92 days, or by mid-June. Chlorophyll levels in excess of 100 μg/l have been reported in Grizzly Bay and the Napa River estuary and greater than 200 μg/l in the San Joaquin and Petaluma Rivers estuaries.

Condition 4 was demonstrated with a series of six flask experiments in the laboratory, six chamber studies (incubation in the Bay) and a large outdoor tank (ecosystem) which was maintained at the SERL laboratory. The flask and chamber studies were described in a preceding section. In the ecosystem successive diatom and flagellate blooms were induced through nitrogen spiking with resulting turbidity and wide DO fluctuations followed by die off of cells with DO depressions below 6 mg/l.

Condition 5 is met by local examples in the Napa River and Petaluma River estuaries in Coyote Creek in South San Francisco Bay and in tidal, fresh water reaches of the San Joaquin River. The first three receive treated sewage and industrial wastes, the last receives principally agricultural drainage. Surveys of these tributaries were described in a preceding section.

Other examples of observed algal problems include the tidal reach of the Potomac River and the James River, both tributary to Chesapeake Bay (23, 24). Other eutrophic conditions in estuaries include green seaweed problems in Pegasis Bay (New Zealand) (14), Chesapeake Bay (16), Boston Harbor (15), in the British Isles (13) and green algal blooms (Nannocloris) in Raritan Bay and Great South Bay and its tributary estuaries (12).

It is concluded that the combined effect of nitrogen enrichment and sediment inflow reduction will lead to higher algal populations in Suisun Bay and western Delta in the future. Figure 15 may be used to determine the range of chlorophyll expected between May-October for a given organic nitrogen level. Nitrogen concentrations projected for Suisun Bay for a Master Drain discharge at Antioch are discussed in Appendix B. Estimated chlorophyll ranges for 1970-2020 for the May-October period are shown in Figure 16.

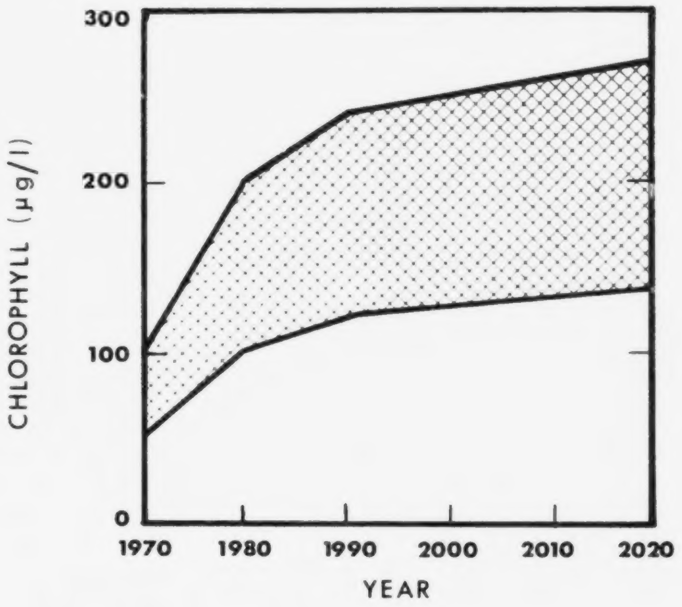


CENTRAL PACIFIC BASINS PROJECT

PREDICTED
NITROGEN—CHLOROPHYLL
RATIO

DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMINISTRATION
SOUTHWEST REGION SAN FRANCISCO, CALIFORNIA

FIGURE 15



CENTRAL PACIFIC BASINS PROJECT

PROJECTED CHLOROPHYLL CONCENTRATIONS

U. S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMINISTRATION
SOUTHWEST REGION SAN FRANCISCO, CALIFORNIA

FIGURE 16

VI. ALGAE—DISSOLVED OXYGEN MODEL

INTRODUCTION

Sanitary engineers have been predicting (DO) concentrations in natural waters containing organic waste for several decades. Relationships between decomposable wastes (BOD) and atmospheric reaeration have been developed and applied using the predictive formulation known as the Streeter-Phelps equation (25). The Streeter-Phelps formula is normally given in differential form as:

$$\frac{dD}{dt} = K_1 L - K_2 D$$

where D is the oxygen deficit concentration

t represents time

L is the ultimate BOD concentration

K_1 is the deoxygenation rate constant

K_2 is the reaeration rate constant

Expressing the oxygen deficit, D as $(C_s - C)$ where C is the oxygen concentration and C_s the concentration at saturation, the above equation may be rewritten as:

$$\frac{dc}{dt} = K_2 (C_s - C) - K_1 L$$

Modifications to the above formula to include photosynthetic oxygen contributions by algae have been proposed by many recent writers; however, these generally assume that the photosynthetic term is a constant or a trigonometric function during the daylight hours (26, 27, 28). Photosynthetic contributions are usually accounted for in these formulations by referring to observed photosynthetic oxygenation patterns rather than to the causal agents, namely algal crops, light and nutrients.

Marine biologists and limnologists have formulated mathematical expressions relating photosynthetic inputs to algal crops and light energy and, in some cases, to other factors including nutrients, temperature and cell shading. A few examples are given by Ryther, (29) Eppley (30), and Suguira (31).

By combining the sanitary engineering formulations involving bacterial decomposition of organic wastes and atmospheric reaeration with an adaptation of marine biology and limnological formulations relating photosynthetic contributions to algal crops and light energy, a general expression for oxygen predictions in an environment containing algae is possible.

The sanitary engineering formulation can be modified to include the effect of algae by adding the two factors, photosynthetic production (P_t) and algal respiration (R_t), to the differential.

$$\frac{dc}{dt} = [P_t - R_t - K_1 L_t + K_2 (C_s - C_t)]$$

Marine biology relationships serve to provide the P and R rates. These rates may be substituted in the above formulation, but the solution of the differential equation is cumbersome. An alternate solution involving a series of simultaneous equations can be used to represent a dynamic DO balance over 24 hours. Each equation is set up to represent a given time increment, and the resulting matrix is then solved for the DO concentrations at each preselected time increment. Specific conditions of algal crop, light availability, water velocity, water depth, decomposable wastes (BOD), temperature, salinity, and algal growth phase (P/R ratio) are established in order to obtain rates for P, R, K_1, L, K_2 and the appropriate DO saturation value (C_s).

For a day divided into 6 four hour periods a set of six simultaneous equations can be developed. Using the basic oxygen balance equation and some rearrangement of terms, these equations result:

$$C_2 = [P_1 - R_1 - K_1 (L) + K_2 (C_s - C_1)]t + C_1$$

$$C_3 = [P_2 - R_2 - K_1 (L) + K_2 (C_s - C_2)]t + C_2$$

$$C_4 = [P_3 - R_3 - K_1 (L) + K_2 (C_s - C_3)]t + C_3$$

$$C_5 = [P_4 - R_4 - K_1 (L) + K_2 (C_s - C_4)]t + C_4$$

$$C_6 = [P_5 - R_5 - K_1 (L) + K_2 (C_s - C_5)]t + C_5$$

$$C_7 = [P_6 - R_6 - K_1 (L) + K_2 (C_s - C_6)]t + C_6$$

Where $t = 4$ if all rates are expressed as hourly functions.

Assuming dynamic equilibrium, $C_1 = C_7$; this means that there are six independent equations in six unknowns:

$C_1 \ldots\ldots\ldots C_6$.

There are several numerical techniques for solution of these equations, the simplest being a sequential substitution.

The method is numerically self-checking since $C_7 = C_1$ should result after the solution is completed.

If the equations are set up for a matrix solution, the variables separate into two parts:

1) A 6 x 6 matrix consisting of diagonal values of 1 and $(1-k_2)$ and 2) a column vector of 6 elements, the sums of P, R, k_1L and k_2 (C_s). Solution of this matrix yields the C_i values.

Figure 17 illustrates the type of DO variations forecast for the same level of eutrophication in three different aquatic systems.

Production and Respiration Rates of Algae

Marine biologists and limnologists working with primary production have related photosynthetic rates to algal crops as measured by chlorophyll pigments. The term commonly applied is "assimilation ratio" which is defined as the maximum amount of carbon fixed per hour achieved under non-limiting light conditions.

The maximum production per chlorophyll unit may occur at some light intensity between 1000-3000 foot candles, depending upon light adaption and the algal type. Curl and Small suggested that assimilation ratios of 0-3 indicate nutrient depletion; ratios of 3-5 indicate borderline nutrient deficiency, and ratios between 5-10 indicate nutrient-rich waters (32). Verduin has reported assimilation ratios ranging from 2.6 to 3.7 based on various studies by others carried out in lakes and marine waters (33). Ryther reports a mean assimilation ratio of 3.7 in his paper on the estimation of phytoplankton production in the ocean from chlorophyll and light data (29). Converting Ryther's mean assimilation ratio to oxygen terms yields 0.0099 mg/l O_2 produced per hour per microgram per liter chlorophyll.*

Dissolved oxygen production and respiration rates were measured directly by FWPCA personnel using natural and artificially enriched San Francisco Bay and Delta water (6). The waters were of varied salinity ranging from nearly pure sea water to fresh water. Oxygen production studies at 20°C ± 2°C and 800 foot-candles light intensity were carried out in a laboratory incubator using both natural algal populations and higher algal crops grown in the nitrogen enriched waters. Respiration rates were obtained from dark bottles incubated in the same apparatus. Incubation periods were usually less than eight hours.

Chlorophyll measurements were made on all samples prior to incubation. Gross oxygen production rates and respiration rates were compared with chlorophyll levels for three types of planktonic algal communities.

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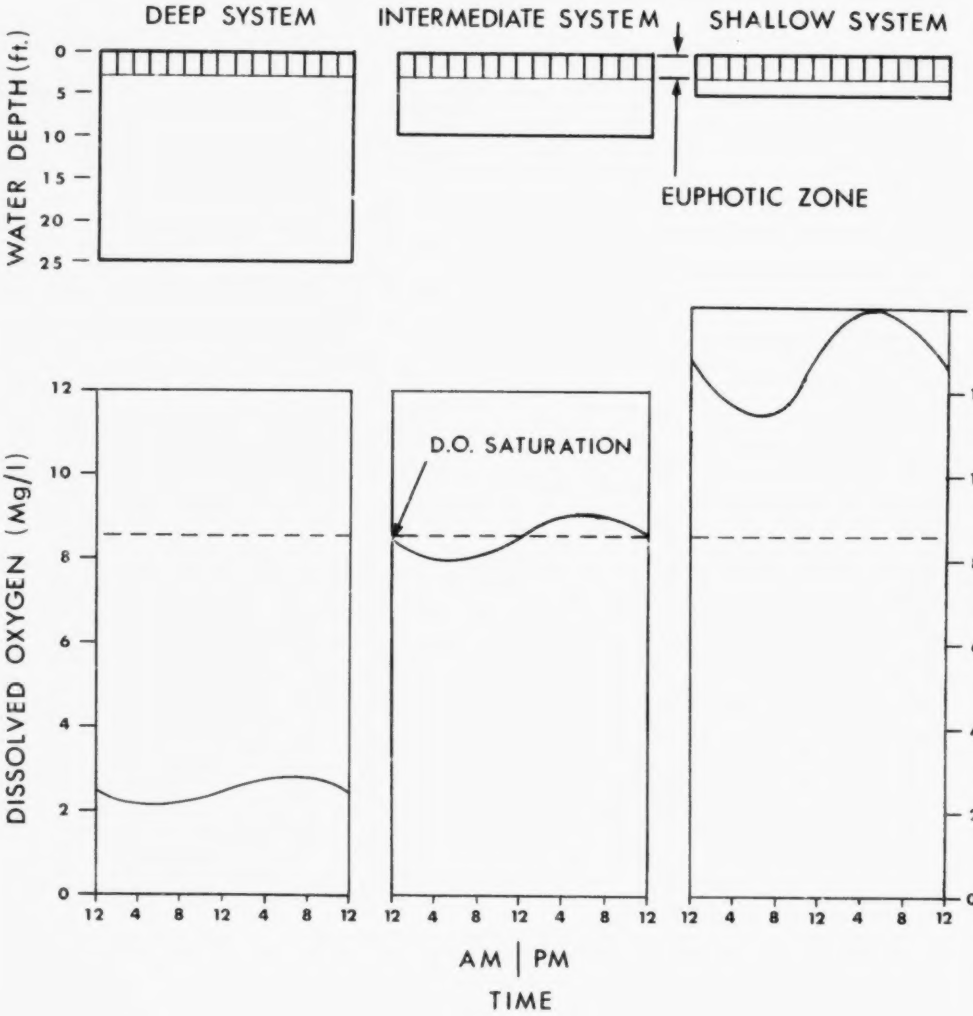
*$P_{max}/\alpha = 3.7(2.67)(1.00) = 0.0099$ mg oxygen produced per liter per hour. Where the photosynthetic quotient (PQ) is assumed to be 1.00, 2.67 is the ratio of oxygen produced to carbon fixed by weight, and α is the chlorophyll concentration in micrograms per liter.



All examples based on constant respiration and gross production for 100 μg/l Chlorophyll.

CENTRAL PACIFIC BASINS PROJECT

PREDICTED
DIURNAL DISSOLVED OXYGEN VARIATIONS

U. S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMINISTRATION
SOUTHWEST REGION SAN FRANCISCO, CALIFORNIA

FIGURE 17

The respiration rate (R), in each case was derived from an algal-dominated community. Zooplankton predators were not abundant in the samples and bacterial respiration was primarily related to "natural" detritus and soluble organics, since the waters used were not heavily contaminated with organic wastes, and algal crops were stimulated with inorganic substrates (usually $Na\ NO_3$).

A statistical analysis of the oxygen production and respiration rate data yielded the following relationships:

$$P_{800} = 0.0059\ \alpha$$

$$R = 0.0013\ \alpha$$

Where P_{800} is the oxygen production rate produced at a light intensity of 800 foot candles and 20°C and R is the respiration rate (both expressed in mg/l/hr) and α is the chlorophyll level in µg/l. The production of oxygen at 800 foot candles is less than the maximum poxxible per unit of chlorophyll and is probably between 50% and 75% of P_{max}. Using these corrections the oxygen produced per microgram of chlorophyll under non-limiting light would be as follows:

$$P_{max} = 0.0088\ \alpha\ (P_{800} = 75\%\ P_{max})$$

$$P_{max} = 0.0118\ \alpha\ (P_{800} = 50\%\ P_{max})$$

These estimates approximate the relationship between chlorophyll and production reported by Ryther and discussed in the preceding paragraphs.

The rate studies carried out by Federal Water Pollution Control Administration personnel were on actively growing algal populations where a P/R ratio of 10 might be considered typical. McAllister et al report that respiration of marine phytoplankton accounted for 10% of gross photosynthesis, except where nitrogen deficiency had occurred, then both P and R were lowered and R was 20% of P (34). Ryther reports that during exponential growth of Chlamydomonas R was 5% - 10% of P, but in nutrient-starved non-growing cultures, R may equal P (35).

Hull has used the relationship of $R = 0.1\ P_{max}$ in computations of oxygen balance in reservoirs (36). The P/R ratio calculated for the FWPCA experiments is 6.8 or 9.1 depending whether P_{800} is assumed to be 75% or 50% of P_{max}. These ratios reflect some bacterial respiration.

Considering the above, the following equations are selected as reasonable estimates of oxygen production and respiration rates (mg/l/hr) for predictive purposes:

$$P_{max} = 0.010\ \alpha$$

$$R = 0.001\ \alpha$$

These rates were considered applicable when the algae are actively growing (log growth phase) and at a water temperature of approximately 20°C.

Light Considerations

Sunlight frequently does not penetrate the full water depth. The depth of light penetration sufficient for photosynthesis (usually assumed as 1% of surface light) is termed the euphotic zone. Light limitation is evident in the lower regions of this zone; while inhibition may occur in the regions of bright light near the waters' surface.

Photosynthetic oxygenation rates through the water mass are assumed (based on work reported by Ryther) to follow a pattern similar to that shown on Figure 18.

Reaeration

Reaeration rates (K_2) may be determined using relationships such as the O'Connor-Dobbins formulation (37).

where $$K_2 = \frac{(D_c U)^{1/2}}{H^{3/2}}$$

D_c = Molecular diffusity of oxygen in water

(0.000081 ft^2/hr @ 20°C)

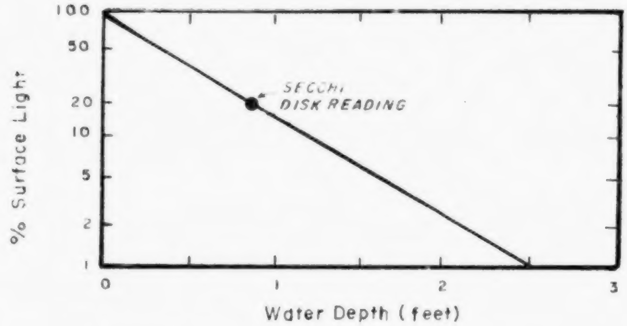
H = water depth (feet)

U = velocity (feet per hour)

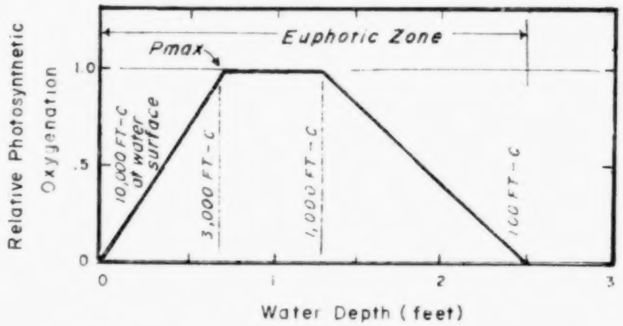
In tidal waters, mean velocity, irrespective of direction is used. The K_2 rate could be varied with the tidal velocity; however, this may be an unnecessary refinement. The effect of wind may be included by increasing the rates 25%, for example, for a 10 knot wind. Deoxygenation resulting from supersaturation of oxygen produced by photosynthesis is assumed to be at the same rate as reoxygenation. This assumption is also made by Howard Odum in his classical paper on the diurnal curve method for determining production and respiration rates in aquatic communities and is the basis for some of the recent work on reaeration carried out at the Robert A. Taft Sanitary Engineering Center.

Example - San Joaquin River at Mossdale Bridge

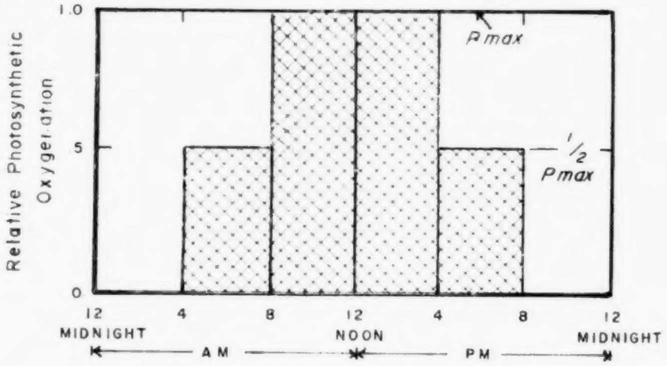
To illustrate the entire oxygen prediction procedure, a numerical example is worked out and the results compared with field DO data. The various oxygen rates were based on the observed chlorophyll, light penetration,



A. Light Extinction Curve (Example)



B. Euphotic Zone and Photosynthesis (Example)



C. Temporal Sunlight Distribution (Example)

NOTE: Item B adapted from Ryther,
Limnology and Oceanography,
Vol. I No. I Jan. 1956

CENTRAL PACIFIC BASINS PROJECT

MISCELLANEOUS
LIGHT DISTRIBUTION
(Examples)

DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMINISTRATION
SOUTHWEST REGION SAN FRANCISCO, CALIFORNIA

37-A

FIGURE 18

stream depth, velocity, and BOD. The computations develop a diurnal curve of DO which may then be compared with the observed DO levels. The example is based on data collected by the California Department of Fish and Game at the Mossdale Bridge on the San Joaquin River (tidal reach) during April 1966. The stream bottom is sandy with no significant benthic deposits of either of algae or decomposable materials. BOD from organic wastes is low in this area during the spring when algal populations dominate the river.

Data inputs:

Chlorophyll (mean) 246 µg/l

Water temperature (mean) 17.6°C

Stream depth (mean) 4.47 feet

Stream velocity (mean) 1.03 fps

Light penetration 2.8 feet (1% level)

Using the relationships previously described, the rates are as follows:

Production. $P_{max} = 0.01 (\alpha = 0.01 (246) = 2.46$ mg/l/hr.

Using a maximum photosynthetic oxygenation rate of 2.46 mg/l/hr at non-limiting light, the average P through the water column during the hours of maximum sunlight energy (8 a.m. - 4.p.m. assumed in example) becomes:

$$\frac{2.46 \times 2.8 \times 0.7}{4.47} = 1.08 \text{ mg/l/hr}$$

use $P = 1.08$ mg/l/hr at times when $P = P_{max}$

The value 0.7 is used to approximate the variation in P through the euphotic depth (2.8 feet) and the total production is assumed well-mixed through the water depth (4.47 feet). No reduction in P was made due to the lower temperature of 17.6°C.

Respiration. Using the equation ($R = 0.001\ \alpha$) the respiration rate resulting from 246 µg/l chlorophyll is 0.246 mg O_2/l at 20°C. The water temperature during the 48 hour period averaged 17.6°C with a range of from 16.4 to 19.5°C. Following Q_{10} theory with a Q_{10} of 2 the R rate for 17.6°C becomes 0.212 mg/l/hr. This respiration rate was assumed to be constant over the 24 hours.

The K_1L function (BOD) may be neglected for in this case, the river respiration is related to the algae and associated bacterial respiration rather than to degradation of sewage. The estimated R rate covers the algae and "natural" bacterial demands associated with the algae. Respiration of zooplankton grazers is neglected.

Reaeration. Reaeration determined by the O'Connor-Dobbins formulation is as follows:

$$K_2(20°C) = \frac{(0.000081 \times 3600 \times 1.03)^{1/2}}{(4.47)^{3/2}} = 0.059/\text{hr.}$$

The K_2 rate may be reduced to correspond with the lower temperature of 17.6°C using the expression:

$$K_T = K_{20}(1.047)^{T-20}$$

yielding a revised K_2 of 0.057/hr.

Calculations. Using the above rates, the DO prediction equations may be written. A four hour time increment was used, leading to seven equations with seven unknowns. The light energy pattern used is shown on Figure 18.

Combining all of the rate values and using the C_s value of 9.6 mg/l the computations are as follows:

at midnight $C_1 = C_7$ (dynamic equilibrium)

$C_2 = [P - R + K2\ (C_s - C_1)]t + C_1$

at 4 a.m. $C_2 = [0-0.212 + 0.057\ (9.6-C_1)]4 + C_1$

at 8 a.m. $C_3 = [0.5(1.08) - 0.212 + 0.057\ (9.6-C_2)]4 + C_2$

at 12 noon $C_4 = [1.08 - 0.212 + 0.057\ (9.6-C_3)]4 + C_3$

etc.

which reduces to:

$C_1 = C_7$

$C_2 = 0.772C_1 + 1.34$

$C_3 = 0.772C_2 + 3.36$

$C_4 = 0.772C_3 + 5.38$

$C_5 = 0.772C_4 + 5.38$

$C_6 = 0.772\ _5 + 3.36$

$C_7 = 0.772C_6 + 1.34$

Solving these equations:

C_1 = 14.2 mg/l @ midnight

C_2 = 12.3 mg/l @ 4 a.m.

C_3 = 12.9 mg/l @ 8 a.m.

C_4 = 15.3 mg/l @ 12 noon

C_5 = 17.2 mg/l @ 4 p.m.

C_6 = 16.6 mg/l @ 8 p.m.

C_7 = 14.2 mg/l @ midnight

These calculated DO values and the observed DO values are plotted on Figure 19. A reasonably satisfactory degree of agreement between the observed and calculated oxygen concentrations is obtained in this example.

Example - Stockton Deepwater Channel

Chlorophyll, temperature and other data for the Stockton deep water channel were used to predict dissolved oxygen levels in a deep, turbid system. These data were gathered by the California Department of Fish and Game during the spring of 1966. The observed DO levels were then compared with predictions.

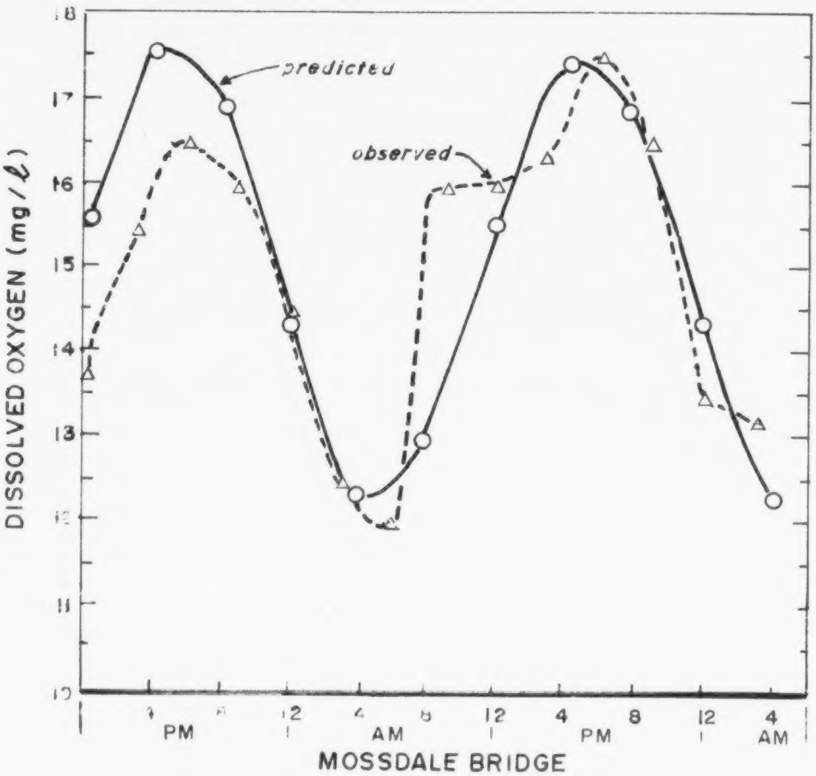
The predicted levels were based on a well-mixed system without consideration of benthic demand. A range of DO predictions of from 8.2 - 9.6 mg/l (midnight values) resulted from a series of calculations using different reaeration rates (ranging from 1/3 - 4 times the rate calculated using O'Connor-Dobbins formula).

A variation in observed DO occurred with respect to water depth with values of 7.1 - 8 mg/l occurring near the bottom at night and from 8.0 - 10.5 mg/l near the surface during the day. At mid-depth (15 ft.) the DO typically was between 8.0 - 9.0 mg/l. The predicted DO range is in close agreement with the observed values.

The equations appear more sensitive to changes in respiration than to changes in reaeration rate. Using only slightly higher R rates DO depressions are predicted which are comparable with the low DO levels (below 3 mg/l) found near Stockton during the late summer and fall.

PREDICTIONS

Dissolved oxygen concentrations were estimated for various conditions of water depth, transparency, chlorophyll and atmospheric reaeration.



MOSSDALE BRIDGE
SAN JOAQUIN RIVER
APRIL 19-21, 1966

NOTE: Observed D.O values furnished by California Fish and Game, Delta Fish and Wildlife Protection Study.

CENTRAL PACIFIC BASINS PROJECT

DIURNAL DISSOLVED OXYGEN VARIATIONS (PREDICTED & OBSERVED)

DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMINISTRATION
SOUTHWEST REGION SAN FRANCISCO, CALIFORNIA

FIGURE 9

Calculations were performed by hand on numerous examples ranging from 5-40 feet in water depth from 0 to 200 μg/l chlorophyll. Oxygen depressions below 6 mg/l were predicted in deeper turbid waters with chlorophyll concentrations above 50 μg/l and below 3 mg/l at chlorophyll levels above 100 μg/l. Increases in water transparency due to reductions in suspended sediment concentrations were obliterated by the turbidity caused by algal cells at higher chlorophyll levels.

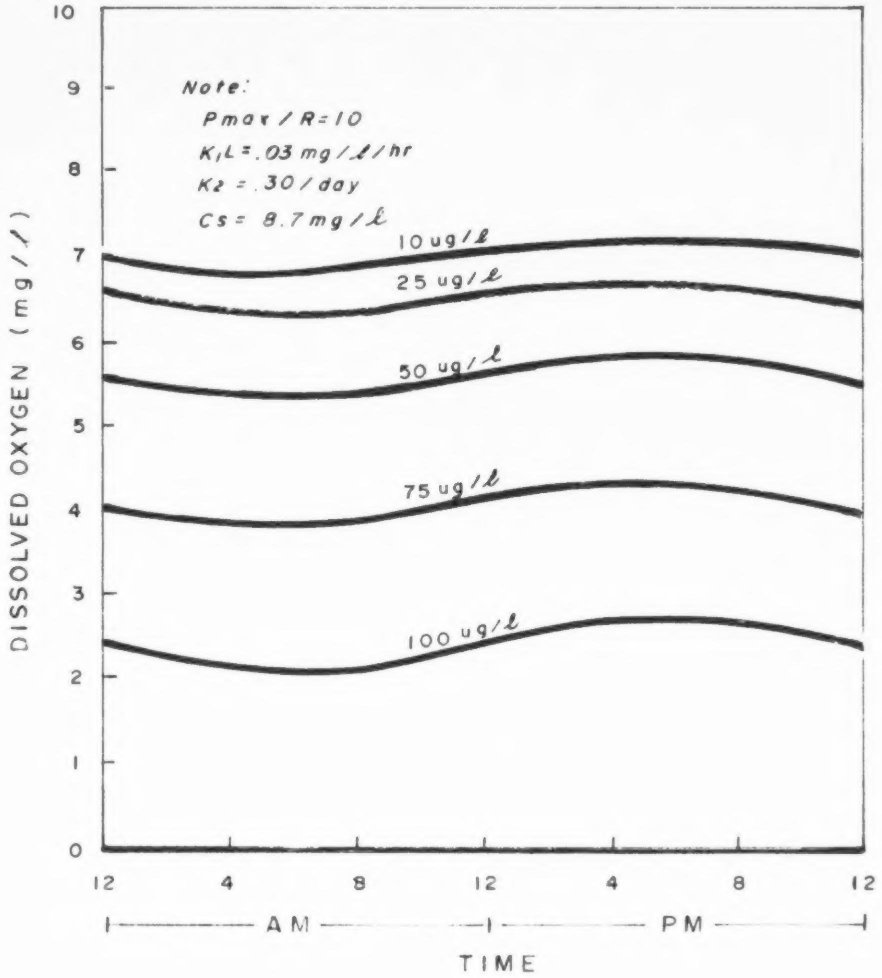
Figure 20 illustrates the effect of increased chlorophyll on DO for a 25 foot channel assumed to contain 27 mg/l inorganic suspended solids (a reduction over present levels). Predictions such as contained in Figure are believed to be overly pessimistic since the calculation gives no credit to tidal mixing. The basic model results were, therefore, not used as final DO predictions and a tidal mixing model was developed to account for mixing of well oxygenated shallow areas with deeper regions of the estuary where DO depressions were expected.

Tidal Mixing Considerations

The basic model of the previous section is a function of six factors and is useful for a unidirectional flow situation. However, a prediction of DO at a fixed station in an estuary must recognize that water quality will also vary as a result of tidal flushing. Changes in waters with tide can be approximated by simulating the history of the waters at the station over the tidal cycles. This is accomplished in an estimate of the tidal exchange and mixing phenomena that explain the station's water quality history. The variables used to explain this mixing are estimates of low and high tide volumes, and estimates of the quantity of water that flow between the several sections of the estuary with each tidal cycle (the tidal exchange).

Two sets of estimates were used to develop a hydraulic model which balanced the tidal exchange flows and tidal volumes for a 5 section estuary simulating San Pablo Bay, Carquinez Straits, Grizzly Bay, Suisun Bay with Grizzly Bay subtracted, and the Delta and areas above Chipps Island. Two sources of well-oxygenated water were assumed as the areas below San Pablo Bay and above the Delta.

A formulation was developed for a 5 section, 4 time period model incorporating the 8 factors of P, R, K, K_2, L, C_s, tidal exchange flows (Q), and low and high tide volumes (V). The interrelationships between the 5 areas and 4 times were expressed as a set of 5 x 4 = 20 simultaneous equations, where the form was similar to that of the simpler model of the previous section, but with more complexity due to the fact that 8 factors are needed for the formulation. Solution for the values of DO follows from the formulation where the values of DO are computed from the product of the inverse of the matrix and the vector of residuals. This particular computation was done with a (IBM 7094) computer.



CENTRAL PACIFIC BASINS PROJECT

PREDICTED DO VALUES
25 Foot Channel
Using Basic Model

DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMINISTRATION
SOUTHWEST REGION SAN FRANCISCO, CALIFORNIA

FIGURE 20

The set of equations corresponding to the Antioch-Delta area can be developed to show how an oxygen balance can be calculated in the tidal situation. The day is divided into 4 parts of 6 hours each corresponding with the half cycles of the tide. Beginning with the high slack phase, the tide begins to ebb and there is a flow from the Antioch-Delta area to downstream areas. During this period there is some freshwater added to this area (section 2), and the P, R, K_1, L and K_2 processes are continuing.

The result of the combination of 5 areas and 4 time periods can be expressed as 20 equations in 20 unknown DO values.

Such a 20 x 20 matrix was solved for 18 combinations of values of P, R, Q, and V. These many solutions are useful for examining the sensitivity of the solution to variations in the parameters. Two different matrices were used, one to represent a situation where the full tidal prism was transported to another section and completely mixed, a second to represent a situation where only half of the tidal prism was transported to another section. Several combinations of photosynthetic production and respiration rates were used, corresponding with high and low chlorophyll values and different P/R ratios. Different relationships of tidal cycle and daylight hours were also evaluated. These variations produced 24 possible combinations as shown below.

$$\underset{(2)}{\begin{bmatrix}\text{Full Tidal Prism}\\ \\ \text{Half Tidal Prism}\end{bmatrix}} \quad \underset{(3)}{\begin{bmatrix}\text{High P}\\ \text{Low P}\\ \text{No P}\end{bmatrix}} \quad \underset{(2)}{\begin{bmatrix}\text{High R}\\ \text{Low R}\\ \\ \end{bmatrix}} \quad \underset{(2)}{\begin{bmatrix}\text{Tide and}\\ \text{Daylight}\\ \text{Phase}\end{bmatrix}} = \begin{matrix}\text{24 possible}\\ \text{combinations}\end{matrix}$$

Eighteen of these possible combinations were solved.

Discussion

Solutions of the formulation above yields 20 values of DO at six hour intervals for five areas. Results from two of the five areas will be compared: 1) Antioch-Western Delta and 2) Grizzly Bay, algal crop levels imposed correspond to 1) 50 and 100 µg/l of active chlorophyll and 2) 50 and 100 µg/l of senesent (or decaying) chlorophyll. In the first case, a P:R ratio of 10 is used; in the second, the P value is zero and R alone is evident.

Predicted DO values are lower in the Antioch region because there are only limited areas from which highly oxygenated shallow waters can mix with the deep channel waters.

Oxidizable organic material and respiratory demands from algae and other living forms could build up in the deep areas near Antioch in at least three ways.

1) Growth of algae in the enriched (and initially clearer) waters of the channel in the spring and summer followed by increases in turbidity caused by the algal cells and associated detritus created in the channel.*

2) Advection of algal cells and other oxidizable organics from shallows and from the Delta channels to the east.

3) Discharge of algal cells from the San Joaquin Valley Master Drain.

The long, warm wastewater drainage canal through the San Joaquin Valley will serve as an incubator for algae, probably of a different character than the natural flora of the western Delta.

Referring to Table 6 below, the Grizzly Bay area of Suisun Bay represents another extreme - a shallow, relatively well-lighted environment (relative to depth). Grizzly Bay waters are somewhat lower in DO under the tidally mixed condition since these waters receive poorly oxygenated waters from deep regions of Suisun Bay. If calculations were performed without consideration of the tidal mixing of the deep water channel, areas of Suisun Bay would be projected to have lower DO levels and the shallow Grizzly Bay area higher DO levels for a given chlorophyll level. Obviously, since tidal mixing between these areas does occur, it is necessary to account for this effect. The importance of the shallow regions in maintaining high dissolved oxygen levels in Suisun Bay cannot be over-emphasized.

TABLE 6

RANGE OF DISSOLVED OXYGEN PREDICTIONS
TIDAL MIXING MODEL

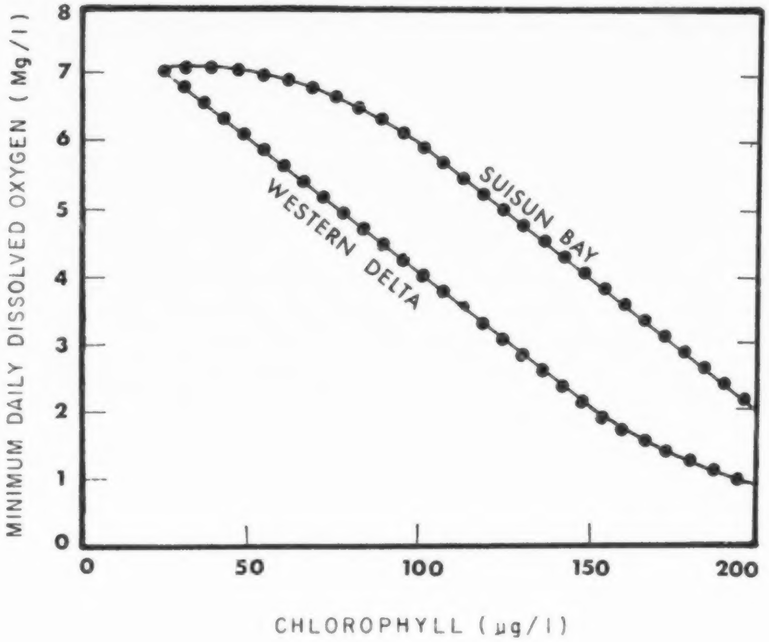
Description of Algal Crop	Predicted Minimum DO Oxygen (mg/l)[1] Antioch	 Grizzly Bay
50 μg/l active chlorophyll	6.2 - 8.1	6.9 - 10.0
100 μg/l active chlorophyll	2.4 - 4.2	5.0 - 10.0
50 μg/l senesent chlorophyll	4.6 - 4.8	5.6 - 6.4
100 μg/l senesent chlorophyll	0 - 1.0	2.4 - 4.2

[1] Ranges result from different tidal mixing assumptions.

---

*In previous sections the depletion of inorganic nitrogen and creation of maximum chlorophyll levels possible under current nitrogen enrichment were cited as typical occurrences in the Antioch area in the late spring and summer.

In conclusion, the projected enrichment of Suisun Bay and western Delta waters is expected to lead to DO depressions during the May-October period, particularly under sustained low outflow conditions. The extent and severity of these predicted depressed DO conditions are dependent on the degree of enrichment and biological response accomplished as well as the physical character of the waters in question. An analysis has been performed to furnish DO predictions for use in evaluating the effect of increased fertilization of these waters on the fishery. The predictions are shown on Figure 21 and attempt to describe the minimum DO condition which could reasonably be expected to occur frequently during the period May-October in the waters of the western Delta and the main channel regions of Suisun Bay. These predictions represent an approximation of the environmental quality expressed in terms of DO and do not pretend to forecast concentrations on any given day. Higher DO levels may be expected during periods of algal growth and lower DO conditions may well exist following decay of an accumulation of a high standing crop of algae, zooplankton, bacteria and associated soluble and particulate organics.



CENTRAL PACIFIC BASINS PROJECT

PREDICTED
DISSOLVED OXYGEN —
CHLOROPHYLL RELATIONSHIP

U. S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMINISTRATION
SOUTHWEST REGION SAN FRANCISCO, CALIFORNIA

FIGURE 21

VII. DISSOLVED OXYGEN AND THE FISHERY

INTRODUCTION

The depressed dissolved oxygen levels that could result from discharge of the San Joaquin Master Drain would adversely affect fisheries dependent upon the San Francisco Bay-Delta system. All fishes (and other aquatic life), both resident in and migrating through the San Francisco Bay-Delta area, will be affected by the anticipated water quality changes in Suisun Bay and the western Delta. Among the various fishes, three species are of prime importance insofar as direct use by man is concerned. These are the king (Chinook) salmon, *Oncorhynchus tshawytscha*, the striped bass, *Roccus saxatilis* and the American shad, *Alosa sapidissima*. Each is anadromous (that is, they migrate from salt to fresh waters to spawn). The only connecting waterways between the ocean and the Sacramento and San Joaquin Rivers are through Suisun Bay and the western Delta. Certain fresh waters of the Delta are important spawning areas for striped bass and the brackish and fresh waters of Suisun Bay and the Delta serve as nurseries for many kinds of young fish.

Some known effects of dissolved oxygen depression on fish and the dependence of these effects on other water quality considerations are summarized to provide a basis for fishery loss predictions.

A survey of the literature clearly indicates that almost any departure from "natural" levels of dissolved oxygen concentration in the water may adversely affect some fishes. In addition, even "natural" concentrations of DO can be inadequate, since they are so inescapably associated with other environmental and physiological variables which alter the need of fish for oxygen. Among these variables are temperature, toxic wastes, amount of available food, reproductive cycle, other dissolved gases, photoperiod and thyroid activity.

In the present study, two major aspects of the effects of DO reduction on fishes are of concern. One is the concentration below which fish die (lethal limit); the other involves the myriad of sublethal and indirect effects. Within the first breakdown, two further subdivisions are: (1) the direct lethality of low DO and (2) increases in toxicity of other elements or compounds in the presence of low DO levels.

The resistance of fish to low DO's also depends upon their acclimatization. Many authorities (38, 39, 40, 41, 42) have pointed out that through gradual acclimatization fish can eventually tolerate oxygen concentrations which are ordinarily asphyxial. To survive at these levels, the fish is required to remain almost completely quiescent. Since activity is, however, a required normal part of fish's life, it is not feasible to try to maintain a healthy population by acclimatization.

Field and laboratory evidence show mortality caused by low DO is particularly dependent upon both the species of fish and the temperature (43). Table 7 lists some reported short-term (or acute) lethal DO concentrations, arranged approximately in order of ascending concentrations.

One of the principal reasons for the relatively wide range of DO figures in Table 7 is that the determination of lethal concentrations is always affected by the particular procedure used. In experiments in which the characteristics of the water are changed by other than the removal of the dissolved oxygen, results may not show an influence due solely to the lack of oxygen, but rather the combined effects of low DO and one or more other factors. Examples of these effects are the increased toxicity to fishes of a variety of substances when the dissolved oxygen concentration is lowered.

For purposes of this study two assumptions, based upon considerable correlative information, have been made. One is that the oxygen requirements for other fishes apply in general to the anadromous species with which this study is concerned. The other is that salmonid and other anadromous fishes in this latitude rank first in order of sensitivity as to their oxygen requirements.

Furthermore, it is reasonable to assume (from a variety of evidence) that the Genus Oncorhynchus, which includes the king salmon, shares the high level of sensitivity of the rest of the salmonid family to DO, temperature and other environmental factors. This should be kept in mind when reference is made to trout in the discussion which follows.

DISSOLVED OXYGEN AND TOXICITY

The San Francisco Bay system continually receives large volumes of municipal and industrial waste effluents. These wastes contain compounds, the toxicity of which usually varies inversely with the concentration of dissolved oxygen. Some of these materials are potassium cyanide (a respiratory depressant) and p-cresol (70), lead and copper salts (71), ammonia (72, 73, 101, 102), synthetic detergents (74), and zinc chloride and napthenic acid (75).

Many of the above materials are known to be present in waste effluents tributary to Carquinez Straits, Suisun Bay and the western Delta. Enrichment of the estuary with attendent algal caused DO and pH changes will increase toxicity hazards to fish and other aquatic life.

TEMPERATURE AND OXYGEN REQUIREMENTS

The dissolved oxygen requirements of fishes are also strongly influenced by the temperature of the water. In general, as the temperature increases,

TABLE 7

SOME PUBLISHED RECORDS OF DISSOLVED OXYGEN CONCENTRATIONS LETHAL TO FISH LIFE

Lethal Oxygen Level (mg/l)	Fish	Water Temperature	Reference
0.2	Warm Water Species	ice covered lake	44
0.2-0.4	Bluegill	0-4°C	45
0.25-0.50	Stickleback	---	46
0.26-1.11	Salmon, Silver	---	47
0.3-1.1	Bullhead, Black	0-4°C	48
0.3(est.)	Bullhead, Brown	30°C	49
0.4	Bass, Smallmouth	---	38
0.525-0.75	Yellow Perch	11-21°C	51
0.63-1.56	Bass, Smallmouth	11-27°C	52
0.68-1.44	Minnow, Bluntnose	16°C	53
0.9	Trout, Brook	9°C	40
1.0	Minnows, Guppies	---	54
1.0	Warm Water Species	---	55
1.05-1.92	Trout, Rainbow	10-20°C	52
1.1	Troup, sp.?	6.5°C	56
1.1	Trout, Brook	11°C	57
1.1	Carp	30°C	58
1.1-1.14	Salmon, Silver	10-11°C	59
1.1-2.47	Trout, Rainbow	10-22°C	52
1.13-2.8	Trout, Brown	6-24°C	60
1.2-2.5	Trout, Brook	19-20°C	38
1.3	Salmon, Silver	16°C	61
1.4	Salmon, Silver	20°C	59
1.4-1.5	Crappie, sp.?	0-4°C	48
1.4-2.8	Trout, Brown	21-21°C	52
1.5-1.54	Steelhead	11-13°C	59
1.52-2.4	Trout, Brook	3.5-23°C	62
1.6-3.4	Trout, Brook	12-21°C	52
1.7-2.5	Carp, Mirror	16°C	50
1.75	Trout, Brook	8-10°C	63
1.8-3.8	Shad, American	21-23°C	64
1.89	Trout, Rainbow	10°C	50
2.0	Salmon, Silver	24°C	61
2.0-2.2	Salmon, Parr	8°C	65
2.2	Carp, Buffalo Fish	---	66
2.25	Yellow Perch & Minnows	20-26°C	67
2.3	Bass, Largemouth	0-4°C	45
2.3-4.8	Bass, Largemouth	0-4°C	48
2.3-2.7	Salmon, King	21-23°C	47
2.64	Trout, Rainbow	29°C	50
2.9	Trout, Brown	---	58
3.0	Salmon, King	---	68
3.0-3.7	Trout, Rainbow	16°C	50
3.0	Freshwater Fishes	25°C	39
3.4	Trout, sp.?	25°C	56
3.74	Carp, Mirror	20°C	50

the DO concentration level lethal to fish also rises. These effects are explained partially by the fact that as the temperature increases, the fish's tissues demand more oxygen and thus respiration increases. The harder the fish "breathes" the greater are the fish's O_2 requirements (69).

Temperature dependence is well exemplified in work by Shaw (76), in which the average oxygen consumption of small salmon and trout increased 400 percent as the temperature was raised from 7° to 20°C. Peak water temperatures occur in the summer in Suisun Bay and the western Delta when DO depressions due to future enrichment are most likely to occur.

DISSOLVED OXYGEN AND FISH PHYSIOLOGY

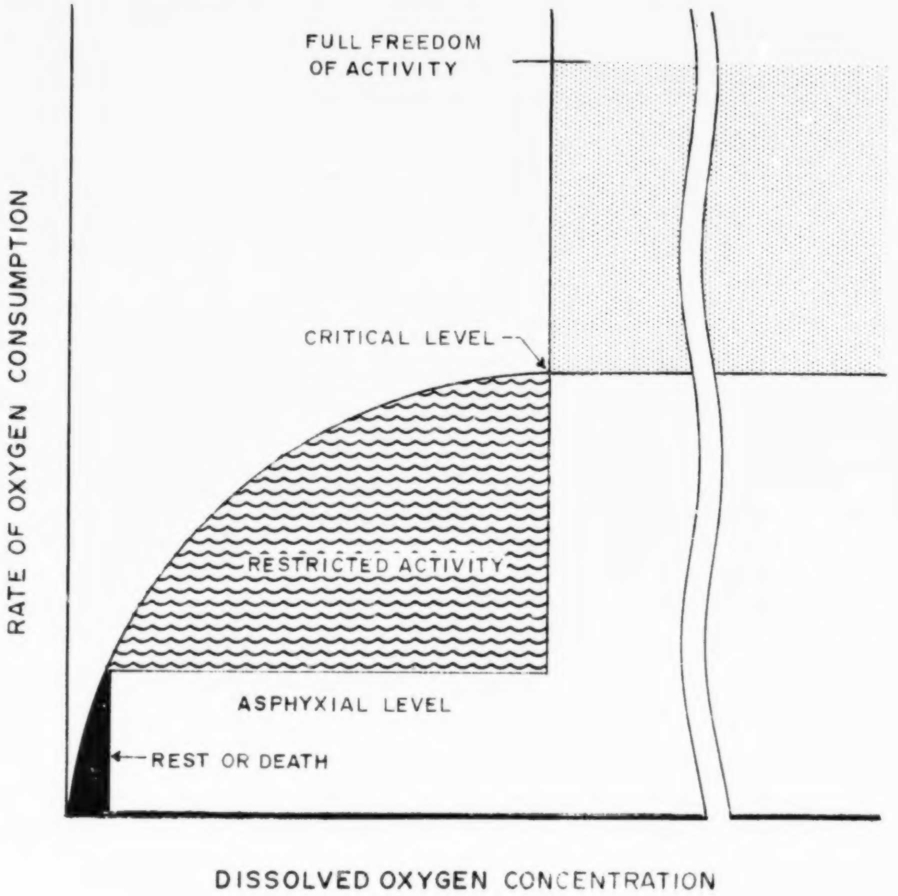
Oxygen Consumption

Fry (77) has shown that the activity of a fish is dependent upon its metabolic rate and that the latter, in turn, is dependent upon the oxygen content of the water. Figure 22 shows a somewhat simplified schematic relationship between oxygen consumption (metabolic rate) and DO and the resultant effect upon the fish's activity. Any reduction in DO reduces the oxygen consumption and hence the activity, and thus places the fish at a disadvantage. Further reduction prohibits all activity and leads eventually to death. Fry has also shown that the activity of brook trout (Salvelmus fontinalis), at 16.67°C can be 100 percent at a DO of 10 mg/l, but drops to only 50 percent at 6 mg/l and to zero at 3.75 mg/l (53). Lagler et al (69) mention that normally active fish are strongly dependent on the oxygen concentration in water, and that the lowering of the oxygen tension (alone) is compensated for only by a reduction in activity, as a result of decreased oxygen consumption.

Beamish (78) has shown that spawning activity in trout (especially the male brown trout Salmo trutta) caused oxygen consumption to increase to the maximum and that this seasonal-sexual response was also found in a number of other fishes as well as limpets (a molluscan form). He ascribed this, in part, to reaction to photoperiod and to thyroid activity. He also showed that starvation among both trout and suckers decreased oxygen consumption (79). If the added effect of decreased available oxygen is considered, the seriousness of other adverse factors may be most significant. In two cases (80, 81) it has been shown that the optimum oxygen consumption of brook trout is dependent on concentrations near or even above air-saturation values.

Development and Growth

Although there is no direct evidence of the adverse effects of lowering oxygen on the development and growth of American shad and striped bass, results with somewhat analogous fishes have been reported (82, 83, 84, 85). The Ontario (Canada) Department of Lands and Forests and Garside found that reducing the oxygen content of water to approximately 50 percent of air saturation caused retardation in development of trout (83, 86).


FULL FREEDOM OF ACTIVITY
CRITICAL LEVEL
RESTRICTED ACTIVITY
ASPHYXIAL LEVEL
REST OR DEATH
RATE OF OXYGEN CONSUMPTION
DISSOLVED OXYGEN CONCENTRATION

CENTRAL PACIFIC BASINS PROJECT

OXYGEN CONSUMPTION
AND DISSOLVED OXYGEN

DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMINISTRATION
SOUTHWEST REGION SAN FRANCISCO, CALIFORNIA

FIGURE 22

Others have verified Garside's findings. Juvenile growth of salmonids is also affected, as determined by Hermann, Warren and Doudoroff (87). They found that under-yearling silver salmon exposed to wide diurnal fluctuations in DO (alternately between 3 and 8 mg/l per day for equal periods) dropped in weight gain to a rate about that expected at a constant 3.5 mg/l (88).

Other laboratory work, however, has shown reciprocal effects. Feeding an unrestricted diet (tubificid worms) increased the percent gain in weight of young silver salmon, (Oncorhynchus kisutch), directly as the dissolved oxygen concentration increased (87).

Swimming

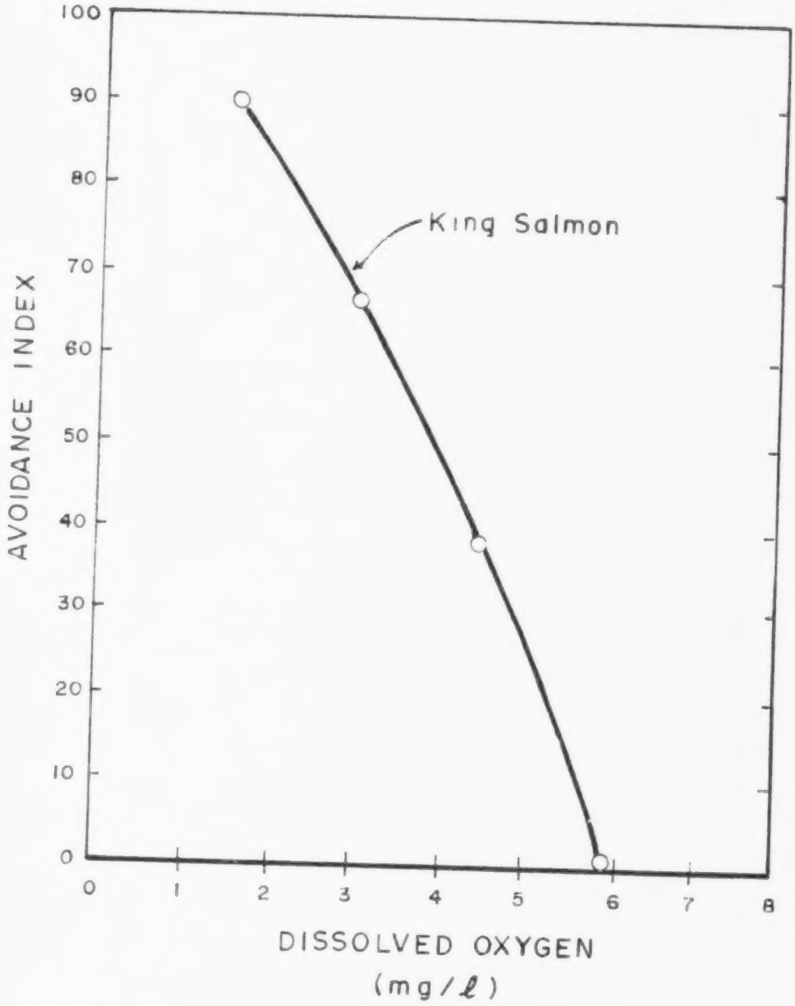
Reductions in swimming speed or endurance affect many, if not all, of a fish's normal activities, including its chances of survival. The effects of lowered DO's on such activities are, therefore, most important. Below about 3 mg/l of DO, Ferguson, as reported by Fry (76), found the cruising speed of yellow perch (Perca flavescens) began to drop sharply. With lower DO's, between 1 and 2 mg/l, swimming may be completely stopped, the width of the critical threshhold being only 0.159 mg/l (88). Swimming endurance in fish may also be significantly reduced (from 90% to 50%) as a result of low DO's (2.5 mg/l) in the presence of suspended conifer-ground wood fiber (89). The significance of this finding in relation to peat deposits in the Delta area is merely suggestive at this time.

Avoidance

Among the many effects on fishes of deficient dissolved oxygen concentrations is one of considerable future significance. This is the ability of fish seemingly to detect and avoid areas of low DO under certain conditions (90, 91, 92).

King salmon have been found by Whitmore, et al, to show definite avoidance as illustrated by Figure 23 at low DO levels with water temperatures ranging from 18.4° to 22.8°C (91). These temperatures lie within the range found in the Suisun Bay-western Delta area during the early part of the fall spawning migration.

Katz and Gaufin (55) found that freshwater fish in winter, when dissolved oxygen concentrations were quite adequate (8.2-12.5 mg/l range), failed to move back into areas which had been intolerable the previous summer because of very low DO 90.2-6.9 mg/l range). Massmann, et al (93) showed that where oxygen in the Rappahannock River dropped "...below 50 percent saturation, the numbers of fish, including striped bass fingerlings, taken in the same area with a haul seine, decreased considerably." It was also shown (94) that under similar oxygen conditions, fish could not be caught in a surface trawl, even though they were abundant in neighboring areas where the DO was higher. If this were to occur in the San Francisco Bay-Delta system, the impact on the sport fishery could be very undesirable.



After Whitmore et al (1960)

DISSOLVED OXYGEN
AND AVOIDANCE

DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMINISTRATION
SOUTHWEST REGION SAN FRANCISCO, CALIFORNIA

50-A

FIGURE 23

Although it is speculative to extrapolate laboratory data to the field, the investigations mentioned above at least suggest the possibility that avoidance could be a causal or corollary factor in the reduction of king salmon runs described by Fish and Wagner (95) in the Willamette River, Oregon and by the California Resources Agency (96) in the lower San Joaquin River, California.

Other Effects

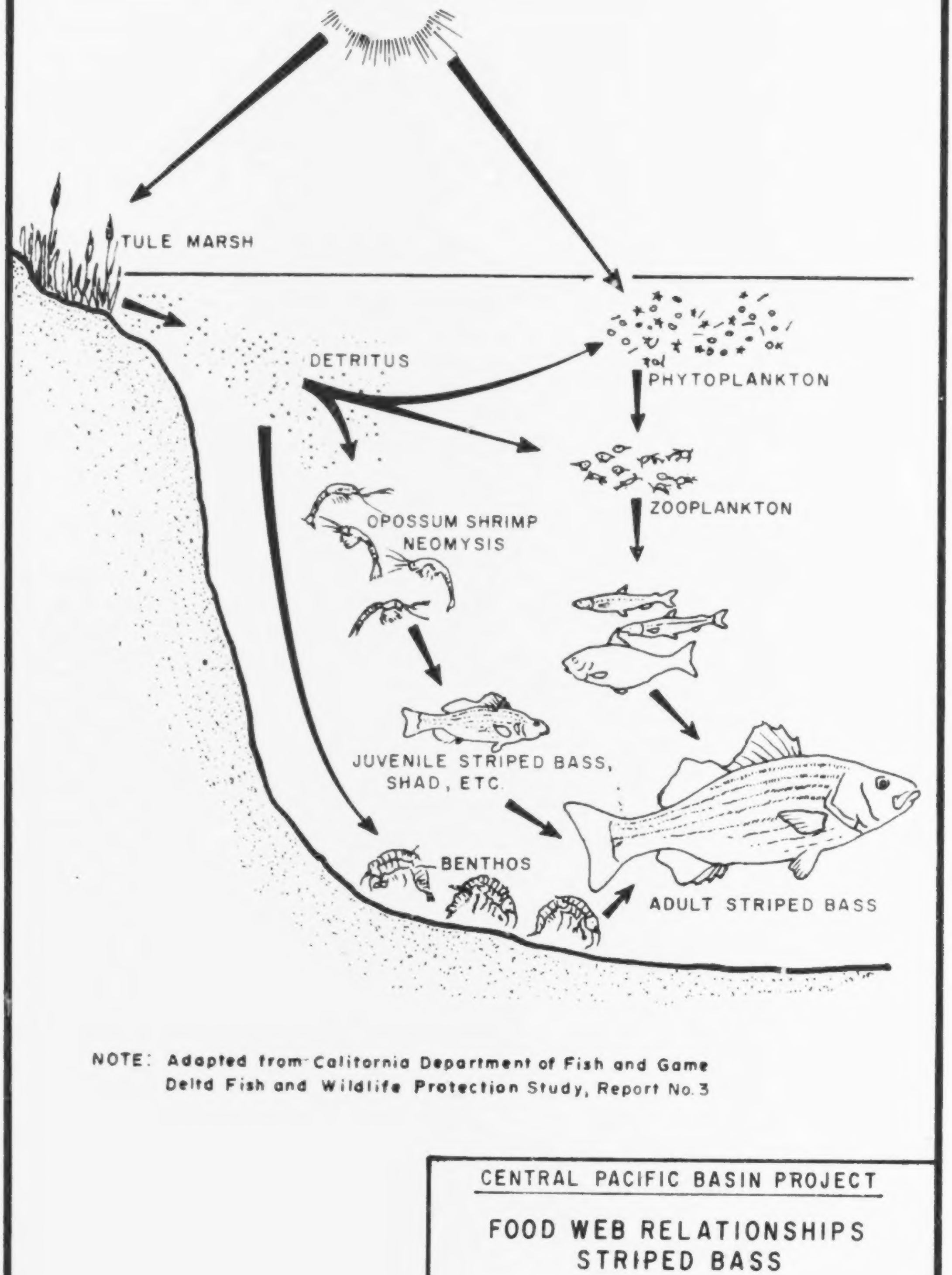
There are many effects on fishes of lowering the dissolved oxygen content of the water which do not properly come under any of the above headings, although they may be intimately related. Alabaster and Robertson (97) report that non-lethal diurnal changes in temperature and DO concentrations between 12.5 and 1.0 mg/l cause certain freshwater fishes to become more active regardless of light. This might be interpreted as leading to a form of avoidance, since they believe avoidance has survival value for fishes that face thermal or BOD pollution.

Lagler et al (69) notes that where excessive CO_2 is present as a result of waste discharges such as sewage effluents, the oxygen transporting ability of the fish's blood loses its efficiency. Experiments have shown that trout die at noticeably higher oxygen tensions when carbon dioxide concentrations approach 50 mg/l (98). Basu (80) found that even with moderate concentrations of CO_2 the active oxygen uptake rates are markedly reduced at oxygen concentrations near the lethal levels. This has been further documented by Doudoroff and Warren (99), along with aspects of pH changes which are not usually related to the effects of lethal levels of dissolved oxygen, except where a lowered pH is caused by acid discharges and a phenomenon known as coagulation anoxia occurs (100).

Sublethal oxygen levels are even considered the causative factor in some diseases of fish. Gottwald (101) attributes a disease called "bluesac" (*Hydrocoele embrionalis*) in rainbow trout (*Salmo gairdnerii*) alevins (young with yolk sac still attached) to inadequate oxygen. A large kill of several thousand threadfin shad (*Dorosoma petenense*), and American shad at Stockton in 1966 was blamed by Montgomery (102) on a bacterial disease (*Aeromonas pique faciens*) which in turn was thought to have been brought on by low dissolved oxygen concentrations at close to lethal levels.

FOOD WEB RELATIONSHIPS

Detritus is important as a food source for many organisms, and bacteria are important in recycling nutrients from the detritus as well as from decaying plants and animals. Algae, however, form the base of the estuarine food web. Diatoms, other phytoplankton, and the zooplankton grazers are essential to the shell and fin fisheries of the San Francisco Bay-Delta system. Fishes represent the top of the aquatic food web. Figure 24 illustrates food web relationships for the striped bass.


TULE MARSH
DETRITUS
PHYTOPLANKTON
ZOOPLANKTON
OPOSSUM SHRIMP
NEOMYSIS
JUVENILE STRIPED BASS,
SHAD, ETC.
BENTHOS
ADULT STRIPED BASS

NOTE: Adapted from California Department of Fish and Game
Delta Fish and Wildlife Protection Study, Report No. 3

CENTRAL PACIFIC BASIN PROJECT

FOOD WEB RELATIONSHIPS
STRIPED BASS

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMINISTRATION
SOUTHWEST REGION SAN FRANCISCO, CALIFORNIA

51-A

FIGURE 24

Fish feed upon various organisms largely on the basis of the availability and abundance of preferred food. In the San Francisco Bay-Delta area the predominant invertebrates include several species of mollusks, crustaceans and worms. Following recent introduction to the Delta area, threadfin shad have multiplied rapidly and striped bass are now found gorged with this forage species.

The Pacific herring, *Clupea pallasii*, together with the northern anchovy, *Engraulis mordax*, and the pond smelt, *Hypomesus transpacificus*, are among the more important forage fishes in the Bay. They are important both as forage for larger game fishes and as fishing bait. Since they are strictly marine forms, they are not found very far upstream from Suisun Bay.

The California Department of Fish and Game reports that in the Delta almost all young fish feed primarily on crustacean plankters. These plankters are known to be vitally important to young striped bass and to young and adult American shad. The predominant food item of many intermediate size fish (particularly striped bass) is the opossum shrimp, *Neomysis awatschensis*. These shrimp, near the southern extreme of their range, are common in the salinity ranges found during summer in eastern Suisun Bay and the western Delta. There is evidence that opossum shrimp requires dissolved oxygen concentrations greater than 7 mg/l and that they are most numerous in the deeper waters, probably because they try to avoid light. The main nurseries for the striped bass are in the deep channels of Suisun Bay and the tidal reaches of the Sacramento and San Joaquin Rivers where the Neomysis shrimp are abundant. The deep turbid channels are the waters most likely to suffer oxygen depressions.

Marshland vegetation is another part of the extensive food web provided by the aquatic environment of the San Francisco Bay-Delta area. This is an extremely important part of the diet of waterfowl. The most preferred and used plant forage species is the "alkali" bulrush, *Scirpus robustus*, which is of intermediate salt tolerance. Waterfowl also consume freshwater-adapted grasses (and their seeds), and, in emergency, will use salt-tolerant species found in the salt marshes of the Bay system. Certain mollusks figure conspicuously in the diet of diving ducks, and the exposed tide flat organisms provide sustenance for many species of shorebirds.

DISSOLVED OXYGEN CRITERIA

Many individuals and organizations have made recommendations as to desired oxygen criteria for fishes (42). In the present study some approximation of such criteria is necessary as a guide in planning certain proposed discharges so that they will adequately protect this particular beneficial use. It is, therefore, worthwhile to examine some of the approaches and investigations leading up to these criteria.

Among the early workers, Plehn (103) listed 10-11.43 mg/l of DO for trout, noting that they showed "some discomfort" at 7.87 mg/l if the water were "warm." Thompson (66), examining the already highly polluted Illinois River and speaking of a warm water group of fishes, said that there was no evidence of any real variety of species at levels below 4.0 mg/l of dissolved oxygen, whereas above 9 mg/l he found the greatest variety or numbers of kinds of fish. This approach is especially interesting in its attempt to answer the general question of what conditions are optimum in the sense that they are preferred by fish life on the basis of actual population sampling in the field. Ellis (39) carried this to its logical conclusion in a study involving 5,809 DO determinations at 982 stations on United States streams in all but four states (Rhode Island, Delaware, Oregon and California) during the summer (June - September). In categorizing the populations of observed fishes, Ellis defined a "good fish fauna" as "... including representatives of the fine fish group (trout, or bass, sunfish, perch, and other spiny-rayed fishes), the rough fish group (suckers, buffalo, and catfish), and the minnow series, in good condition at the time the samples were taken." The results showed that 96 percent of the good fish fauna stations contained at least 5 mg/l DO. This figure became the criterion for DO recommended by Ellis at a temperature of 20°C or above, providing other adverse factors were not also present. Brinley (104) on the basis of his Ohio River fish population sampling confirmed Ellis' work. Later, Ellis (105) emphasized that the 5 mg/l DO requirement was for "warm-water" types, and that the requirement for cold water fishes was even higher. In 1949, Southgate (106) summarized the DO requirements of fishes and concluded that no clear general statement on the minimum concentration of dissolved oxygen required for fish life can be made, since requirements vary with temperature, species and age of fish, the concentration of other substances in the water and other factors.

From the early thirties until recent years, considerable attention was devoted to determining short-term lethal limits of DO for fishes, i.e. that concentration below which there would be mortality, as noted in Table 6. Many fisheries biologists, notably Tarzwell (107, 108), protested this approach because these low concentrations did not provide for the continuously adequate well being of the fish nor the maintenance of fish food organisms.

During the last two decades, however, attention has been focused more on the effects of low, but sublethal levels of DO. From these studies has emerged a number of orders, regulations, promulgations and simple recommendations as to the permissable levels of DO for the protection of fish life. Shaw (76), in making recommendations for holding trout in hatcheries, used 5 mg/l. Fish and Wagner (95), referring to the oxygen "block" in the Willamette River, Oregon, stated that DO concentrations of less than 5 mg/l keeps the fall run of king salmon from completing its spawning migration.

In 1955, the Aquatic Life Advisory Committee of the Ohio River Valley Water Sanitation Commission published its First Progress Report (109) wherein certain water quality standards for fish life were proposed. This report established some important precedents. Among these was the recommendation that there should be not less than 5 mg/l of DO during 16 hours of any 24 hour period and at no time less than 3 mg/l, but for up to 8 hours in any 24 hour period the DO could drop to between 5 and 3 mg/l. This was for warm water game fish. For the so-called "rough" fish, the absolute minimum proposed was 2 mg/l. It was specifically emphasized that this was not to be regarded as suitable for game fishes of the family Salmonidae, but no recommendations for the latter group were made. These standards were highly criticized by Doudoroff and Warren (97), who noted in their own experiments the adverse effects of low DO's during those 8 hours of a diurnal fluctuation in which the DO could drop below 5 mg/l.

At this same time, the California Division of Water Resources (Department of Public Works) (110) referred to a communication by the California Department of Fish and Game to the Central Valley Regional Water Pollution Control Board on August 23, 1954 recommending a minimum of 6 mg/l of DO and 85 percent saturation for fish life in the San Francisco Bay system. McAllister (111), in a study conducted for the U.S. Bureau of Sport Fisheries and Wildlife, made the same recommendation. Fry (53) held to the 5 mg/l level for what he called the "long term value." The California Department of Water Resources, in publishing its own DO recommendations (8), departed from the Department of Fish and Game figures and proposed 5 mg/l as satisfactory for migrating (meaning here salmon) fishes, as well as the minimum saturation of 85 percent. Brett (112) took exception to the use of saturation figures. He discovered that in air-saturated fresh water, oxygen became a limiting factor for active metabolism in a group of yearling sockeye salmon, (Oncorhynchus nerka), when the water temperature exceeded 15°C. He concluded, further, that any reduction below complete saturation (above 15°C) could be expected to reduce maximum activity. Doudoroff and Shumway (113) also warned against using saturation values, since they provide only for the maintenance of the lowest concentrations of oxygen at precisely these temperatures at which the highest concentrations may be needed by fish.

Quite recently Talbot (55) stated that he believed, judging from work on other species, that 4 mg/l of DO may not be too low for successful striped bass production. He did not, however, further qualify this statement. In a like view, Tarzwell (107) gave 6 mg/l as the minimum for "good salmonid production."

Dissolved oxygen objectives used in a 1964 study of the Willamette River, listed the following (114):

A minimum of 7 mg/l DO for salmonid fish rearing.

A minimum of 5 mg/l DO for salmonid fish migration (the 5 mg/l may need revision as a result of future studies).

More than 6 mg/l DO for growth and propagation of fish, shellfish and other aquatic life.

Dissolved oxygen standards for the Tidal Potomac include a median value of 6.5 mg/l in reaches to be protected for propagation of desirable species and 5.0 mg/l median value for hardier species. A minimum DO of 4.0 mg/l was also set in the Potomac standards (115).

The Public Health Service (116) used a DO of 5 mg/l as the minimum concentration that the warm water fishery of the Stanislaus River could tolerate without damage.

After discussion with the Fish and Wildlife Service the tabulated relationships between DO and fishery damage was developed.

TABLE 8

ESTIMATED FISHERY DAMAGES FROM LOW DISSOLVED OXYGEN CONCENTRATIONS*
(Warm Water Fishery-Stanislaus River)

Dissolved Oxygen (mg/l)	Damage Factor % Destroyed
5.0 and above	0
4.5 - 4.9	5
4.0 - 4.4	15
3.5 - 3.9	30
3.0 - 3.4	60
below 3.0	100

* USPHS - Water Supply and Water Quality Control Study, New Melones Project, Stanislaus River Basin, California, January 1965.

It should be emphasized that the foregoing table was developed for a warm water fishery. Cold water forms, including salmonid fishes, require higher DO concentration than warm water species.

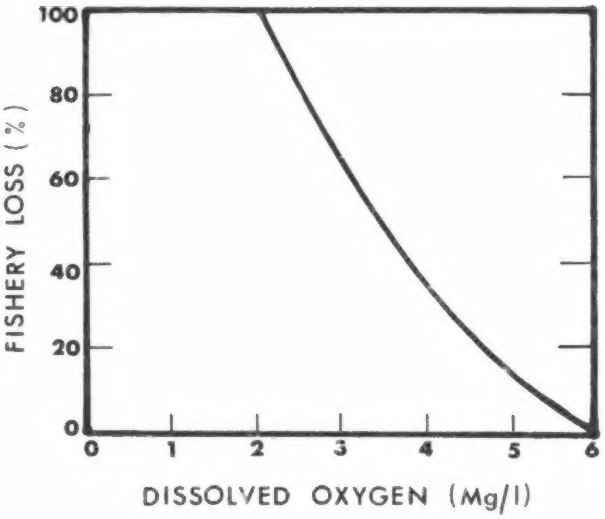
The California Department of Fish and Game (117) has reported that in the San Joaquin River in 1965, a few salmon migrated through the Stockton deep water channel with about 5 mg/l dissolved oxygen, but most did not migrate upstream until the dissolved oxygen exceeded 6 mg/l.

It is readily apparent from the foregoing review that through the years, as workers have developed more information, the DO levels they have recommended have risen and usually with considerable special qualification.

Based on the literature search to date (no reliable field data is available), a minimum dissolved oxygen concentration of 6 mg/l has been arbitrarily selected, for the purposes of this study, as the environmental level at which the anadromous fishes of the San Francisco Bay-Delta system will be adequately maintained. As this report was being prepared, word was received from the California Department of Fish and Game that it now appears that the opossum shrimp is most likely the limiting factor for striped bass and that this crustacean requires between 7 and 8 mg/l of oxygen for survival. This is mentioned here to emphasize that the 6 mg/l figure applies directly to fish life rather than the rest of the food chain. Fishery losses (below present levels) are expected at DO levels less than 6 mg/l and these losses are expected to vary exponentially from 0% at 6 mg/l and 100% at 2 mg/l. See Figure 25.

The use of the exponential loss approach is in line with curves already established by research on the effects of lethal and sublethal DO levels on fishes.

Projected losses apply only to that portion of the particular anadromous fishery which is in a region of projected low DO during times when low DO is expected.



CENTRAL PACIFIC BASINS PROJECT

PREDICTED
FISHERY SURVIVAL

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMINISTRATION
SOUTHWEST REGION SAN FRANCISCO, CALIFORNIA

FIGURE 25

VIII. FISH POPULATIONS

INTRODUCTION

The impact of dissolved oxygen depressions on Bay-Delta fishery resources will depend upon the severity of the depressions and the numbers of fish exposed. Both the seasonal and spatial distribution of fish were considered in estimating the population exposed since the projected dissolved oxygen deficiencies problems were limited to the May-October period in Suisun Bay and the western Delta region. A fish population model approach was developed using dissolved oxygen-fishery loss relationships shown on Figure 25 and assumptions based on available data on anadromous fish distributions within the Bay-Delta system.

FISH DISTRIBUTIONS

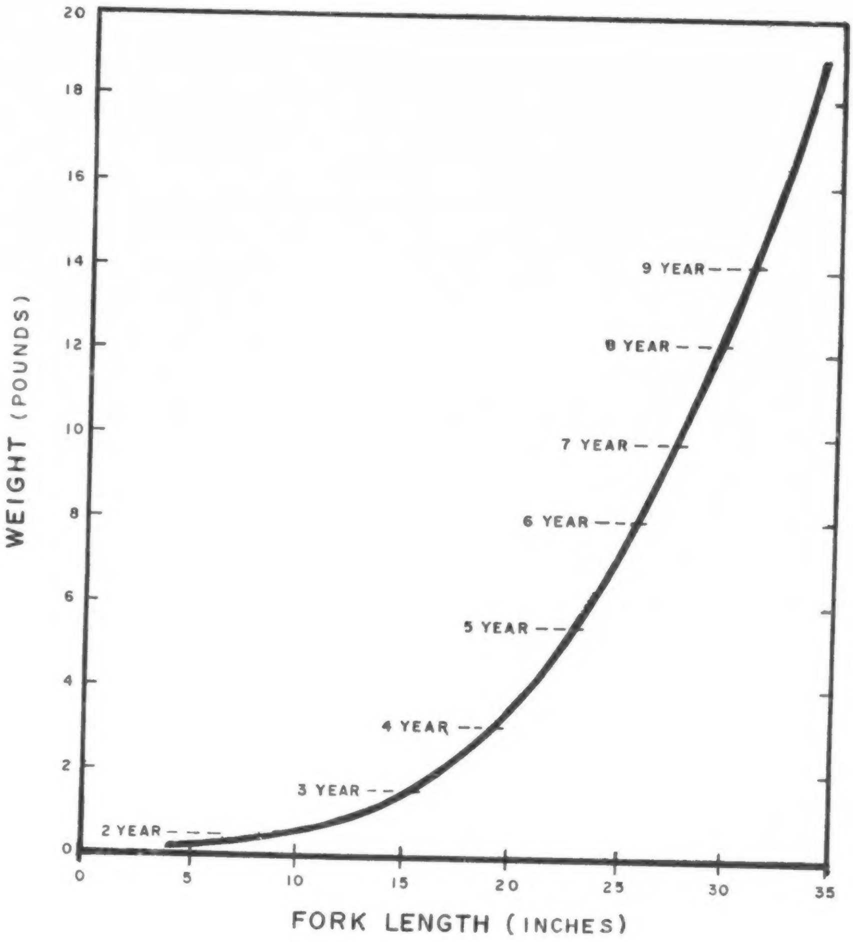
There are over 188 species of fishes in the San Francisco Bay-Delta complex. Among these are three important anadromous species: the striped bass, king salmon and the American shad. These three species have been singled out for consideration primarily because of their economic importance.

It is the anadromous characteristic of these species which makes them particularly vulnerable to degraded water quality in the Bay-Delta system, for they are not merely residents in a single area, but pass through different parts of the system during one or more stages in their life history. Thus, they may be exposed to regions of poor water quality with considerably more frequency and at what may well be more vulnerable periods in their development.

In order to evaluate potential damage to these species, consideration must be given to questions of where and when these fish are found in the system, and for how long. These questions require more information than is presently available. Partial answers, however, may be provided from data on the life histories and records of these three fishes within the Bay-Delta system.

Striped Bass

The striped bass was introduced to California waters in 1879 (118), and rapidly assumed prominence in the recreation and economy of the State of California (119). Striped bass grow to a large size, reaching at least 78 pounds in California and 125 pounds on the East Coast. The young bass, four inches long at the end of its first year, grows rapidly (Figure 26) reaching 10 inches at the end of the second, 16 inches at the end of the third and 18-20 inches at the end of the fourth year (120). From this point growth is about three inches per year, a 10-12 year old being about 36 inches long and a 20 year old reaching 48 inches and about 40 pounds.



From: Robinson, John B., 1960 California Fish and Game, 46(3): p.283

CENTRAL PACIFIC BASINS PROJECT

STRIPED BASS
LENGTH, WEIGHT, AND AGE
RELATIONSHIP

DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMINISTRATION
SOUTHWEST REGION SAN FRANCISCO, CALIFORNIA

57-A

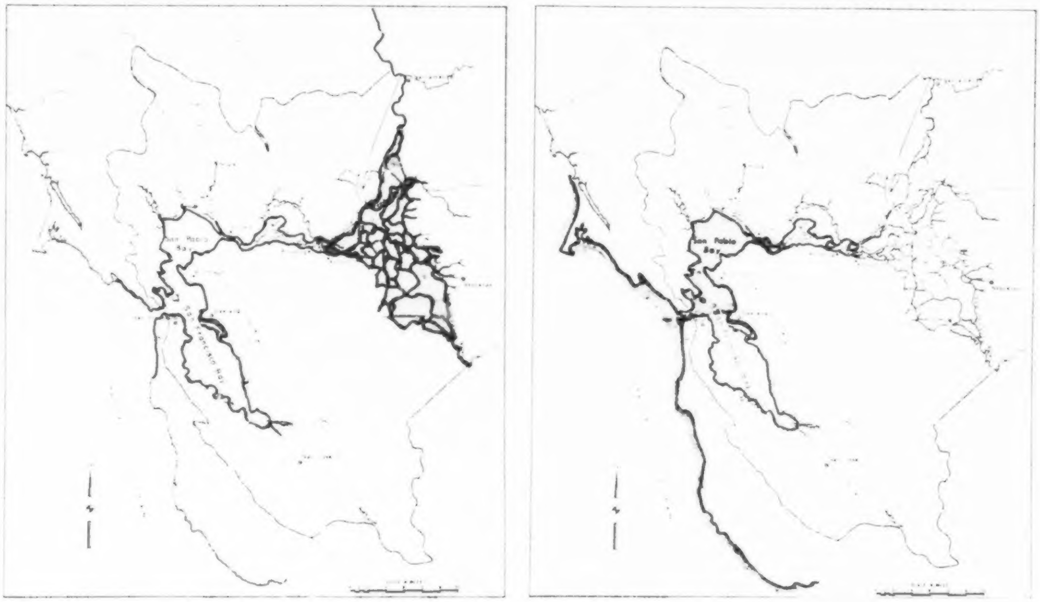
FIGURE 26

Maturity is reached by the female bass at about 22 inches in length (5 years of age), while most males are mature at 11 inches and 2 years old. In the first season of maturity, the female may release up to 25,000 eggs as compared with an 8 year old's 1,250,000 eggs and an estimated 10,000,000 for a 75 pounder. The eggs are slightly heavier than water, but currents keep them in suspension. They hatch in about two days depending on the water temperature. Striped bass prefer flowing freshwater for spawning. Spawning, which occurs in the spring, takes place upstream from Pittsburg, mostly in the Delta portion of the San Joaquin River and in the Sacramento River from the Delta northward to above the mouth of the Feather River. The distance the spawners run upstream is governed by the rate of rise in water temperature; the slower the rise, the further upstream the fish move before spawning (122, 123). Spawning is usually completed by early June.

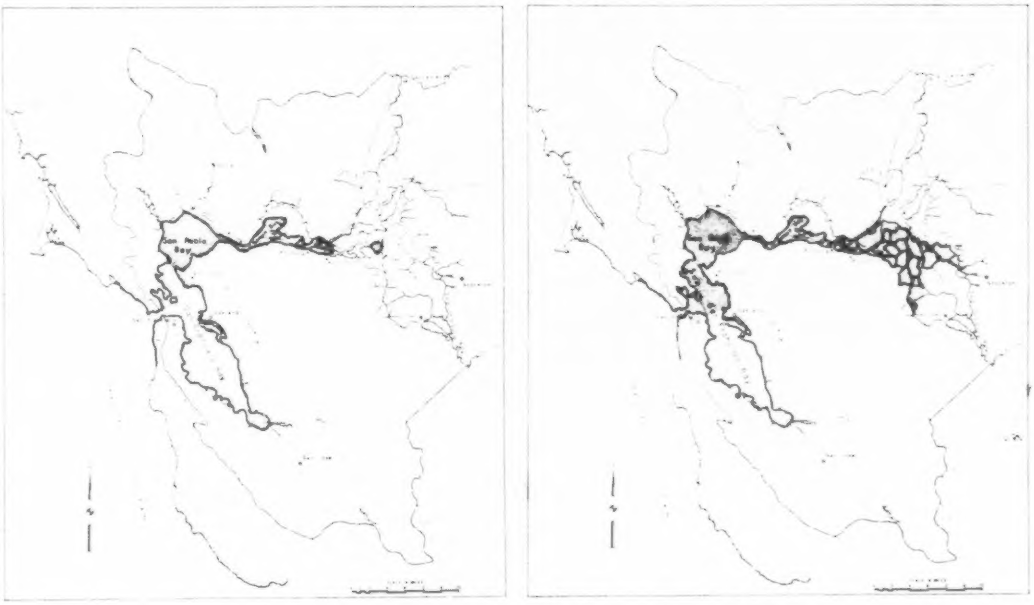
The adult stripers return downstream to San Francisco Bay and adjacent areas of brackish or salt water after spawning. The young stripers spend their time in the Delta nursery areas, especially the lower San Joaquin River, eventually becoming part of the adult migratory pattern, usually after they reach 12 to 16 inches in length, and thus the cycle continues.

Although the effects of water quality upon the various organisms making up the food chain of the striped bass may be highly significant (123), for the purposes of this report attention is being directed primarily to the locations of fish populations. This is broken down by the four seasons of the year in the Bay-Delta area for different sizes of striped bass: adult, young bass (7-17 in. long) and juveniles (17-30 in. long). The distribution varies enormously but, nevertheless, a rather general trend can be discerned.

The distribution of adult striped bass exhibits a fairly definite pattern. In the spring, the majority of these fishes are in the Delta area from Pittsburg upstream in the Sacramento River to above Butte City, the distance upstream depending upon the water temperature (122,124). Their distribution at this time is governed by the need to spawn in running freshwater of suitable temperature. By summer, the adults have moved downstream, westward of Suisun Bay, and are widely dispersed throughout the Carquinez Straits, San Pablo Bay, upper San Francisco Bay and the Pacific Ocean (125). There is an upstream migration in the fall, with many adults in San Pablo Bay and Carquinez Strait in October. By November they are in Suisun Bay and to a lesser extent the western Delta, especially Franks Tract. In the winter the adult striped bass are found scattered throughout most of the Delta and westward including San Francisco Bay where the largest part of the adult population appears to stay until spring. These movements are portrayed in Figure 27, but it should be emphasized that the actual migrations are not as precisely limited either geographically or seasonally.


San Pablo Bay
San Francisco Bay
San Pablo Bay

SPRING SUMMER


San Pablo Bay

FALL WINTER

CENTRAL PACIFIC BASINS PROJECT

SEASONAL DISTRIBUTION OF ADULT STRIPED BASS IN SAN FRANCISCO BAY & DELTA AREA

DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMINISTRATION
SOUTHWEST REGION SAN FRANCISCO, CALIFORNIA

FIGURE 27

The patterns of distribution of the young-of-the-year (age class 0) and the juvenile (age class 1) striped bass are much less well-defined. Data mostly from Ganssle (126) and Sasaki (127, 128) show that in the spring the young fish seem to prefer Suisun, Honker and Grizzly Bays, while the juveniles are rather more spread out with the greatest concentrations being found in the lower San Joaquin River.

By summer the young bass spread from the Suisun Bay area to the adjacent areas of both the western and central Delta including 25% in the Sacramento River Delta between Collinsville and Isleton and 10% in the San Joaquin River Delta from Collinsville to Vernalis. The majority (about 65 percent) remain in the Suisun Bay area. During the remainder of the year, all but 10-15 percent are found in Suisun Bay, the others being scattered upstream from Collinsville. Sampling performed to date by the California Department of Fish and Game generally yielded less than one percent downstream from San Pablo Bay, and in the Bay itself at most only two percent during the spring.

Age class 1 juvenile striped bass are also for the most part found in the Suisun Bay area throughout the year. Their distribution is, however, more generally widespread than the young-of-the-year (YOY) fish. In the Suisun Bay area, numbers of these one-year old fish build up to about 40 percent during fall and winter, while the numbers in the Sacramento and San Joaquin River Delta are dwindling. By winter some 25 percent are also found in San Pablo Bay and about 10 percent in San Francisco Bay. This indicates a general downstream movement toward San Francisco Bay. Figures available thus far do not include any sampling in the rivers above the Delta, so to what extent these juveniles may also disperse upstream during various seasons of the year is not known (129).

In conclusion, significant features of striped bass distributions in the Bay-Delta system include the spring spawning of adults in the fresh waters of the Delta and rivers, the return of the adults to the Bay after spawning, the presence of juvenile bass in Suisun Bay and the Delta all summer and the importance of Suisun Bay as a nursery ground for the yearling striped bass.

King Salmon

King salmon, known as chinook salmon in Oregon and Washington, is native to the Pacific Coast of the United States. According to Jordan (130), it was first recognized by Steller in 1731, but was an important food item of the Indians long before the arrival of the first Spanish explorers (119). In California, the major drainage basin used by this anadromous fish is the Sacramento - San Joaquin River system (131), and it is with this system that we are most concerned because of the proposed locations of a major waste discharge.

King salmon, like striped bass, have been known to exceed 100 pounds, but their average weight at spawning is about 20 pounds. In a very general way, their life history is as follows. Adults, usually three to five year old fish ranging from 5 to 40 pounds, migrate through the San Francisco Bay and Delta area en route to the cool, gravel-bottomed upper reaches of the Sacramento River system and certain tributaries of the San Joaquin River which are still accessible.

Arriving on the parental spawning grounds, the female selects a spot where she digs a redd (nest) in which she deposits up to 5000 eggs. All the while she is closely attended by the male who fertilizes the eggs right after they are extruded. The eggs are covered with gravel by the female and left to develop. Unlike other anadromous fishes, both parents die soon afterward, none surviving to spawn a second year. The eggs hatch in about 50-60 days, depending upon the water temperature, and the emerging young wriggle to the surface of the gravel in the following three to four weeks. Within a few additional weeks, most of the young fish begin their migration downstream to the ocean. In the sea they eat voraciously and grow at a rapid rate, reaching maturity in about three to five years. At this age they begin their upstream spawning migration, as did their parents, and whenever possible, travel to the same tributary or headwater in which they were born, there to repeat the life cycle once again.

If it were only the single migration pattern, albeit at a somewhat different time of year, the movement of the king salmon would not be sufficient reason to differentiate it from other anadromous species. The significant difference, however, lies in the fact that there are three separate races of king salmon, each of which migrates and spawns at a different time of year.

Of the three races, the most important in terms of numbers is that known as the "fall run," the estimated number varying roughly from year to year between 100,000 and 600,000 with the average being about 360,000 (132). These fish, as adults, start their spawning migration in August, the run peaking in late September and continuing into January. Spawning takes place mostly in November and December, almost immediately upon their reaching the spawning grounds. It is believed that the offspring of this run move downstream in the late spring, although Heubach (133) shows the run peaking near Redding, California in mid-February.

The "winter run" of king salmon number only about one-sixth that of the fall run. These fish start moving into the San Francisco Bay-Delta area in October and reach the spawning grounds by December. They do not spawn at that time, however, usually waiting until May or June (134). Young winter run fish move downstream primarily in the fall.

The "spring run" is the smallest race, being less than one-tenth the number of the fall run. They ascend to freshwater during March through July, spawning from September to early November. Their young are the earliest to migrate downstream, the movement generally taking place from December through March. Although both fall and winter run king salmon use the San Joaquin River to a minor extent in addition to the Sacramento River, the spring run is practically extinct in the San Joaquin.

Although the above data would indicate that downstream migration ends rather abruptly by June 1st, it does not reflect the additional time it takes for the young fish to reach the estuary and San Francisco Bay itself. Fish population sampling by several separate groups (126, 135, 136, 137) yielded the greatest numbers of young salmon in this area in June.

The fact there is so much movement up and down the Bay-Delta system by the three races of king salmon at various stages in their life histories is illustrated in Figure 28. This shows not only that all of the salmon must move through the area in both directions, but also that there are some salmon present at all times of the year.

American Shad

Probably the first fish species to be introduced in California waters was the American shad, Alosa sapidissima, in 1871 (138). This anadromous species increased tremendously in abundance, and for years supported a million-pound commercial fishery. Sport fishing for shad has become a rapidly growing activity since 1950, and in 1957 the commercial fishery was legally closed (119).

The life history of the American shad, especially as it applies to the West Coast of the United States, is not nearly as well known as that of either the striped bass or the king salmon. An adult shad may reach 14 pounds and 30 inches (139, 140), but the average is closer to four pounds (141). Sexually mature adults, of which the males are three years old and the females four, spawn in the fresh waters of the Sacramento River and its tributaries from April through June. The San Joaquin River is not, however, used extensively for spawning by these fish. Depending upon size, females may produce from 100,000 to 150,000 eggs which are slightly heavier than water and non-adhesive. Lehman (142) reported a calculated estimate of 4,680,000 eggs for a single Hudson River fish, but such a large number is not reported elsewhere in the literature. The male fertilizes the eggs as they are released by the female. There is no nest. The eggs are carried along by the current for 4 to 15 days before hatching, depending on the temperature of the water (143). Although the adult fish do not necessarily die following their first spawning, as do the Pacific salmon, few live to perform the spawning act a second time. The young fish immediately return to the ocean where they grow to sexual maturity.

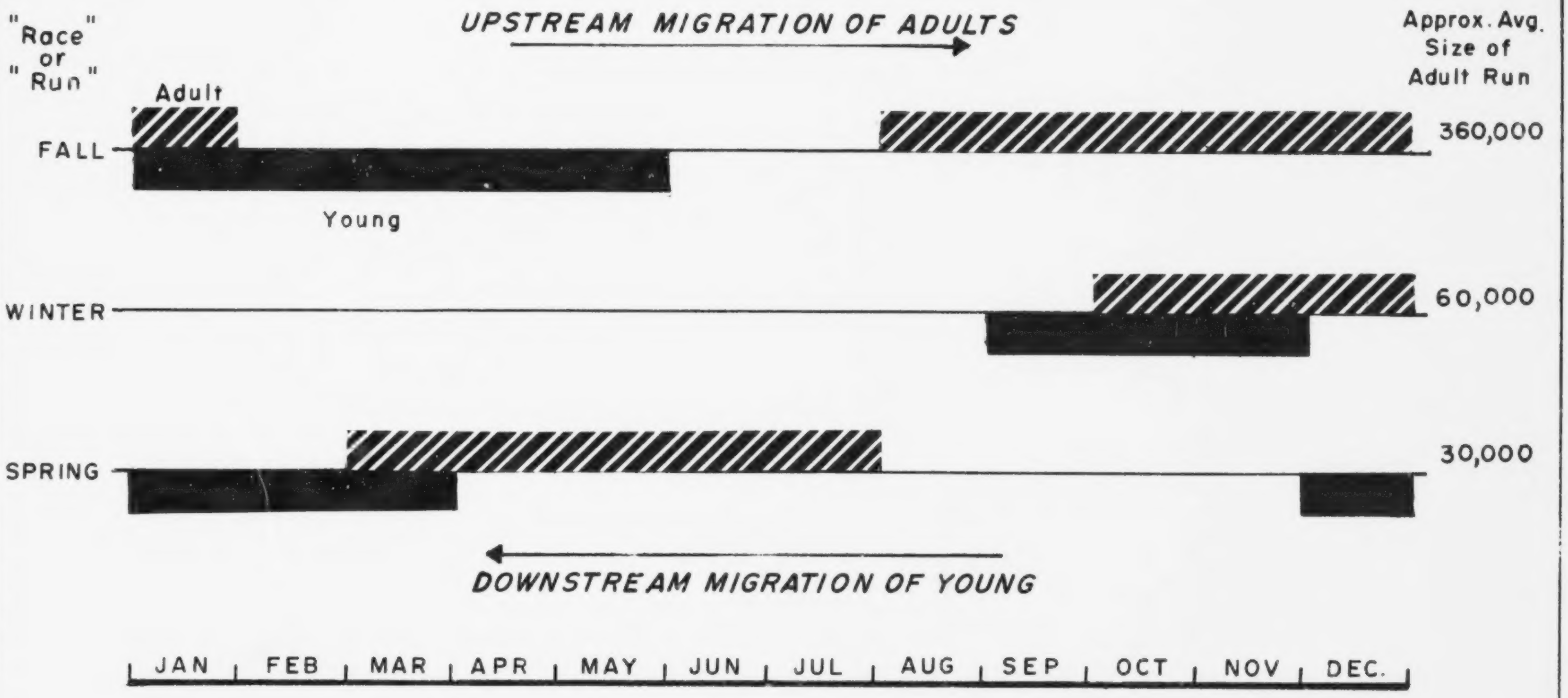


Figure modified from Heubach (133)
Size of Run from Hallock & Fry (131)

CENTRAL PACIFIC BASINS PROJECT
SEASONAL MIGRATION PATTERN
THREE KING SALMON RUNS
SACRAMENTO-SAN JOAQUIN RIVER SYSTEM

DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMINISTRATION
SOUTHWEST REGION SAN FRANCISCO, CALIFORNIA

FIGURE 28

The migratory habits of American shad are rather obscure. It is believed that adult shad leave the ocean only in response to the spawning urge (144). Fish enter San Francisco Bay as early as February and reach their peak concentration in the Delta during April and May (145). By June, they have reached the Redding area of the Sacramento River (146). After spawning they return rapidly to the sea, many dead adult fish being observed along the way at this time. The young shad begin moving downstream soon after hatching and, from September through November as the weather cools, they leave the Delta and gradually enter salt water (147, 148). Once in the ocean the shad appear to scatter and probably to seek deeper waters. Few are found by commercial fishermen, regardless of gear or fishing location.

FISH POPULATION MODEL

The seasonal and spatial distribution of the three anadromous fishes selected for evaluation were reduced for computational purposes to two seasons and four zones within the estuarine system. Distribution patterns of each age class were considered in the skeletonized migration patterns. Each of the three species were treated differently because of basic differences in spawning areas, seasons and life cycles. Table 9 summarizes the distribution patterns.

TABLE 9

ANADROMOUS FISH - DISTRIBUTION PATTERN

FISHERY	AUTUMN	WINTER	SPRING	SUMMER
STRIPED BASS				
Adults	Bay & Delta	Bay & Delta	Spawn in Delta	Bay & Ocean
Young	Bay & Delta	Bay & Delta	Delta	Delta & Bay
KING SALMON				
Adults	Spawn in rivers and die	Immature in Ocean	Adults	In Ocean -----
Young	Ocean	Eggs Maturing in Rivers	Fingerlings Move Downstream From Rivers	
AMERICAN SHAD				
Adults	Ocean	Ocean	Spawn in Rivers	Return to Ocean or Die
Young	Move toward Ocean	Ocean	Fingerlings Move to Delta and Bay	

Assumptions

The two seasons adopted were May-October (6 months of warm-dry weather) and November-April (6 months of cool-wet weather). The May-October season is considered as the most probable time for adverse water quality conditions to occur since these are the months of minimum outflow, highest algal activity, warmest water and highest waste loadings.

Four zones within the Sacramento - San Joaquin River estuarine system were selected along the route of migratory fishes. Moving upstream from A-D, these zones are:

A. San Pablo Bay and below
B. Suisun Bay
C. Western Delta
D. Central Delta and upstream

The "critical" zones were considered to be in Suisun Bay (B) and the western Delta (C) based on the predicted dissolved oxygen regimines for these regions. San Pablo Bay (A) and the balance of the Delta (D) were considered as "Safe" zones where dissolved oxygen levels were not critical either because algal growth (and associated respiration and decay) was expected to be low (Area A) or where reoxygenation factors (reaeration, photosynthesis) were expected to be more significant than respiratory demands (Area D).

Using the relationships of dissolved oxygen and fishery detriments (See Figure 25) each fishery dependent on Areas B and C was exposed during the May-October period to increasingly greater detriments as higher nutrient levels and associated environmental conditions were selected. At dissolved oxygen levels below 2 mg/l in zone B or C the migratory fishery resource dependent upon May-October water quality conditions in those zones was not expected to survive. Losses would be expected to begin at DO levels below 6 mg/l. Zones B and C are presently nursery and acclimatization areas as well as the only thoroughfare between the salt water to the west and the freshwaters to the east.

Young striped bass are important in the diet of older striped bass and the abundance and migration of adults must affect the survival of the young. Cannibalism, therefore, is a factor in determining population densities for striped bass. Egg production by striped bass is sufficiently large to permit some reductions in spawning stock without necessarily reducing young production by the same ratio. As indicated earlier one mature female striped bass may produce a million eggs in one season; salmon usually produce several thousand eggs per female fish. Thus, the numbers of young produced each year (YOY or age class 0) are assumed to be independent of the adult population.

Striped bass survival included consideration of the distribution of yearling and adult fishes (all year classes above 1) and the young of the year (YOY). One half of the yearling and adult striped bass population was assumed to pass through zones B or C during the May-October period. The other half of the adult population was assumed to have spawned and reached zone A before May. In the yearling class, one fourth of the fishery was subjected to zone B and one fourth to zone C and the remaining one half stayed in the Delta through the critical period.

King salmon distribution assumption was that one half of the fingerling salmon passed through the critical zones B and C before May and the remainder were subject to detriments between May-October. Adults were all assumed to reach their spawning grounds in the rivers where their mortality is natural.

Of the American shad one half of the spawning adults and one half of the downstream young of the year were assumed to be in the critical zones between May and October.

Model Development and Example

The effect of exposure of each year class to low dissolved oxygen levels can be calculated from an assumption of mortality rates for each year class. The cumulative effect of the depressed oxygen levels can be calculated through the various age classes considering the particular spatial distribution of the young and older fishes.

Development of the population model:

Natural survival rate (x_t) = 1-mortality rate

$x_t \leq 1$

Pollution survival rate (y_t) = 1-pollution mortality rate

$y_t \leq 1$

Assuming three age classes before the adult stage (YOY, 1-2, 2-3) the corresponding population ratios are:

pop. (1-2) = (pop YOY) $x_t = 0$

pop. (2-3) = [(pop YOY) xt = 0] $x_t = 1$

or = (pop YOY) x0 x1

pop. (3-4) = pop (YOY) $x_0 \; x_1 \; x_2$

etc.

The effect of pollution is to decrease the survival rate by the factor y_t.

Hence:

pop (1-2) = (pop YOY) $x_0\ y_0$

pop (2-3) = (pop YOY)$(x_0y_0)(x_1y_1)$

pop (3-4) = (pop YOY)$(x_0y_0)(x_1y_1)(x_2y_2)$

etc.

Defining an adult as any fish over three years old we have this total population of adults:

(pop _ 3 years) = (pop YOY) $x_0y_0x_1y_1x_2y_2\ [1+x_3y_3+$

$x_3y_3x_4y_4+x_3y_3x_4y_4x_5y_5$ .. etc ..]

If we assume $x_3y_3 = x_4y_4 = x_5y_5\ldots$ then the population of adults becomes:

pop adults = (pop YOY)$(x_0x_1x_2)(y_0y_1y_2)\ \frac{1}{(1-x_3y_3)}$

Since we assume that the population of young (YOY) is constant and that x_0, x_1, x_2 and x_3 are independent of pollution, we have a simple expression for the effects of pollution which incorporates the effect on each age class:

Population of Adults = (Constant)$(y_0y_1y_2)\ \frac{1}{[1-x_3y_3]}$

For striped bass, using $x_3 = 0.5$ (an assumption based on a future harvest of 40% of the adults and allowing 10% more for other factors) we find for $y_0 = y_1 = y_2 = y_3 = 1$ (or no effect from pollution) that the population of adults is:

Pop. adults = $1^3\ \frac{1}{[1-.5]} = 2$

For relative comparison the population of adults under non-polluted conditions is made to equal one by multiplying the above expression by 0.5. Thus, the relative of a fishery such as the striped bass may be expressed by:

Relative survival (RS) = $0.5\ (y_0y_1y_2)\ \frac{1}{(1-0.5y_3)}$

The combined distribution pattern and fishery survival assumption yield the relative survival of each fishery under the given assumptions. An example of the calculations for relative survival of each fishery will illustrate the steps necessary to arrive at the relative fish populations.

Example of computation of relative fish population

Conditions - Nitrogen level - 4 mg/l

From Figure 16 at a 40:1 organic nitrogen-chlorophyll ratio, the maximum chlorophyll would be 100 µg/l.*

From Figure 21 Dissolved Oxygen level in critical areas -

Zone B (Suisun Bay)	6 mg/l
Zone C (Western Delta)	4 mg/l

From Figure 25 Fishery Loss

Zone B (Suisun Bay)	0%
Zone C (Western Delta)	35%

*Assumes essentially all N becomes organic N during the critical period (May-October).

Striped bass relative survival (RS) is computed on the basis of the distribution patterns of the young of the year, and the older fish.

Young of year (YOY) $y_0 = 0.5\ (1.0) = 0.5\ (.65) = .83$

Year Class 1, 2, 3 etc. $y_1 y_2 y_3 = 0.25\ (1.0) + 0.25\ (.65) + 0.5(1.0) = .91$

$$\text{Striped Bass RS} = 0.5(.83)(.91)^2 \left[\frac{1}{1-.5(.91)}\right] = 0.63$$

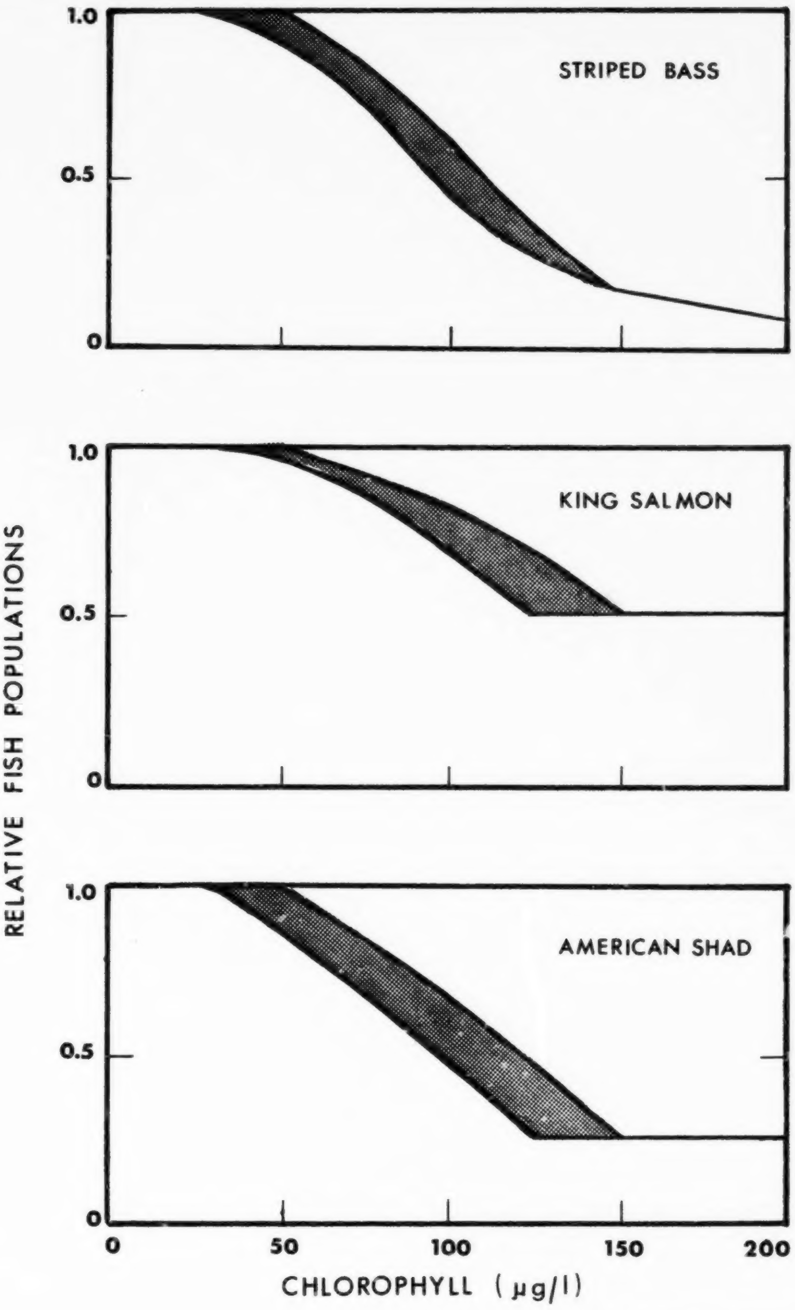
King Salmon relative survival included consideration of the downstream migrants only. Thus the relative survival becomes:

$$RS = 0.5(1.0) + 0.5(.65) = .83$$

American shad young and adults are both subject to exposure to degraded areas of the estuary. Therefore:

$$RS = 0.5(1.0) + 0.5(.65)^2 = .68$$

Figure 29 shows the predicted relative fish populations for the range of chlorophyll levels shown on Figure 16.



CENTRAL PACIFIC BASINS PROJECT

RELATIVE FISH POPULATIONS
VS
CHLOROPHYLL

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMINISTRATION
SOUTHWEST REGION SAN FRANCISCO, CALIFORNIA

FIGURE 29

IX. FISHERY VALUE DETRIMENTS

INTRODUCTION

The relative survival of the three anadromous fisheries under different conditions of nitrogen enrichment can be translated into economic terms. The decline in fishery populations affects the demand and the derived value of the fishery. The sports angler catches fewer fish, and as a result enjoys his experience less with the result that there are fewer fishermen and an overall reduction in fishing effort. These consequences of declining fishery lead to some variations in evaluating the economic consequence of this decline. The predicted fishery detriments (not including intangible values) for the years 1970-2020 are shown on Figure 30. The procedures used to estimate the economic losses relate to the basic value of the sports fishery, calculated as the product of the demand (measured in angler days) and benefit (measured in dollars per angler day as a function of species). The potential demand in future years is estimated from future population predictions by:

Demand for fishery = (k)(Population)

where k is a per capita use constant

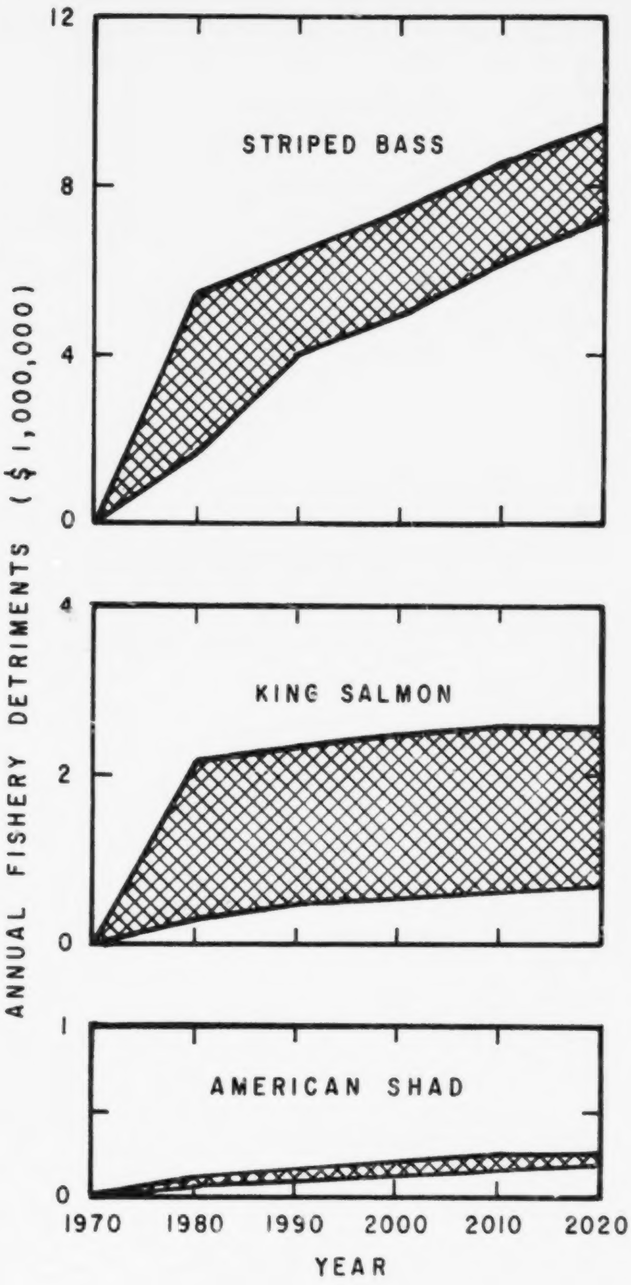
Potential demand may be modified by a consideration of decreased catches per angler. These factors are incorporated in the fishery demand model. Examples will serve to explain the specific calculations and assumptions for each anadromous fishery.

TABLE 10

ANGLER SUCCESS RATIOS*

Year	Striped Bass	King Salmon	American Shad
1960	.50	.588	1.5
1970	.333	.588	1.5
1980	.311	.560	1.5
1990	.263	.529	1.5
2000	.247	.500	1.5
2010	.225	.470	1.5
2020	.222	.441	1.5

*Success Ratios (SR) expressed as fish per angler-day from Skinner's Report to FWPCA (149).



CENTRAL PACIFIC BASINS PROJECT

PROJECTED FISHERY DETRIMENTS

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMINISTRATION
SOUTHWEST REGION SAN FRANCISCO, CALIFORNIA

64-A

FIGURE 30

Fishing pressures have been related to population using a value of k .335 day per capita per year (based on per capita use data 1930-1960). Angler success ratios (legal fish caught per angler day) have been developed for the San Francisco Bay fisheries and these reflect a decline in success as total angling pressures increase. Table 10 presents angler success ratios for San Francisco Bay-Delta fisheries as developed by Skinner (149).

The change in fish expected to be caught in the future can be calculated using relative fish population data, allowable harvest rates, projected success ratios and fishery demand estimates based on population projections. The allowable harvest rate represents the maximum annual catch, which will not cause a decline in the fishery resource.

STRIPED BASS

Using the data in the example of relative fish population computations, the striped bass catch is derived as follows:

> The example using 4 mg/l nitrogen at a 40:1 nitrogen-chlorophyll ratio (100 µg/l chlorophyll) corresponds with the lower limit of projections for 1980. Using the 1980 Bay-Delta median population estimates from Appendix A the reductions in striped bass fishery harvest become: 1980 Fishery Demand = .335 (7,167,000) = 2.4 million angler days. Skinner (149) adjusts 1980 demands to 2.6 million angler days to reflect other factors.

Assuming no decreases in the adult bass population (estimated at 3 million fish) the fishing pressure of 2.6 million angler days would produce a harvest of 810,000 legal size striped bass (using a S.R. of .311 for 1980 from Table 10).

Actually a decrease in fish population is forecast corresponding to a relative survival of 0.62 which reduces the adult bass population to 1.86 million fish. On this basis an annual harvest of 810,000 fish would represent 43.2% of the adult population, a higher harvest than the 25% - 30% now reported and more than the 40% maximum harvest considered by Skinner (149). Maximum harvest was established (based on Skinner) as 40% of the striped bass adults in 2020 and 35% in 2000 and 30% in 1980. On this basis a permissible harvest of the 1.86 million bass remaining in 1980 would be 560,000 or 250,000 fish less than the demand of 810,000 fish. The lost striped bass catch is then translated to an economic loss following the logic below.

In 1980 a striped bass fisherman-day yields .311 fish/day; therefore, a loss of 250,000 harvested bass causes a loss of 800,000 striped bass fisherman days and alternate recreation must be found. At $3.50 per fisherman day (150) the most that loss could be is 2.4 million dollars per year, but this figure does not reflect the fact that alternative recreational opportunities exist. What is surely lost is the 250,000 striped bass which could have been harvested. The striped bass catch could be rated in terms of their worth as commercial produce only (say $.20/lb) at an average weight of five pounds per fish (i.e. $1.00/fish) or $250,000 per year. The first figure (2.4 million/year) exaggerates the recreational fishing value and the second ($0.25 million/year) undervalues the recreational experience by considering only the commercial worth of the fish. A fairer basis is necessary. The basis used here in the evaluation of sport fishing recognizes that the value per fisherman day includes two separate components -- (1) the value of the experience of fishing whether or not a fish is actually caught and (2) the value of the fish caught in a recreational experience. A striped bass fisherman day has minimum value as an outdoor experience -- say $1/day (based on values quoted for warm water fishing, and other recreational experiences). The striped bass itself is considered worth at least $4.00 when caught in a recreational experience. On this basis the loss in 1980 of 250,000 striped bass, and of 800,000 recreation days of fishing would correspond to a loss of $1.0 million in recreational striped bass fishery value, and $800,000 in striped bass fishing experience, or a total of $1.8 million/year. This then is a more representative measure of the recreational

TABLE 11

STRIPED BASS FISHERY DETRIMENTS*

Year	Unimpaired Sport Fishery @		Sport Harvest Lost		Sport Use Lost		Annual Detriment	
	Use	Harvest	Low Loss	High Loss	Low Loss	High Loss	Low Loss	High Loss
1970	2137	713	--	--	--	--	--	--
1980	2600	810	250	738	805	2370	1805	5320
1990	3447	906	516	328	1960	3150	4020	6500
2000	4058	1001	623	917	2520	3720	5010	7400
2010	4887	1100	740	1010	3290	4490	6250	8520
2020	5395	1200	864	1104	3890	4980	7350	9400

*Use in thousands of angler days
Harvest in thousands of fish
Detriment in thousands of dollars

@Projected by Skinner (149)

loss -- The difference between the $1.8 million loss and the $2.4 million total recreational value for 800,000 recreation days reflects the additional cost of recreation experience deferred from striped bass fishing to other similar activities. This evaluation assumes alternative recreational opportunities exist although the cost of these alternatives are not reflected in the estimates of fishery detriments. Table 11 summarizes the fishery detriment calculations for striped bass for the years 1970-2020.

KING SALMON

King salmon sport fishery detriments are computed in a similar manner using the population projections to determine sport fishery demand and success ratios (Table 10) to determine salmon catches associated with the projected demand. Relative survival levels as calculated were then used to determine the differences between projected fishery demands and the amount of this demand, which can be satisfied under different degrees of eutrophication. A king salmon fishing experience was assumed to be worth $1/day and a legal size king salmon caught in a recreational experience (average weight 10 lbs.) was assumed to be worth $10. Commercially harvested salmon were valued at 35¢ per pound or $3.50 per ten pound fish.

The king salmon fishery (sport and commercial) was assumed to be operating efficiently with the present population exploited near capacity (149). The present harvest was set at 600,000 fish of which 16% are sport harvest (149). The harvestable ocean salmon population was assumed to drop by 25% by 2020 as a result of both urban growth and water developments in California (149). Success ratios (Table 10) reflect this population drop. By 2020 the sport harvest is expected to represent 40% of the total catch. On this basis, commercial salmon fishing is expected to fall off even without consideration of the reductions in harvestable salmon.

The effect of reduced fish populations resulting from water quality degradation was evaluated on two bases: (1) considering the reductions were first felt by the commercial fishing industry with no change in sport harvest so long as some commercial fishing was possible (low detriments), and (2) decreased sport fishing harvest with commercial reductions (other than those due to urban and water development) occurring only after the sport fishery was lost (high detriments).

To give a specific example using the 1980 conditions again, the salmon fishery sport catch as related to population by Skinner is:

1980 king salmon sport fishery demand = .0361 days/cap/yr.
(7,167,000) = 259,000 fisherman-days

The projected 1980 demand is reduced 5% to recognize the effect urban growth and water developments are expected to have on the king salmon fishery. This effect was assumed to continue to change by 5% each decade reaching 25% in 2020.

The estimated 1980 recreational use is then revised as:

.95 (259,000) = 246,000 fishermen-days

A success ratio of .56 fish per fishermen day has been projected as per Table 10 . This yields an annual king salmon sport catch of 138,000 fish in 1980. The commercial demand also increases with population, but this demand cannot be satisfied with the projected fishery populations. In 1980 the total harvestable king salmon is roughly 570,000 fish or 95% of the present estimated annual average catch of 600,000 fish. The commercial catch could possibly absorb all of the 570,000 fish or the fish remaining after the sport harvest i.e. 432,000 fish.

Projected relative fish populations due to eutrophication as calculated for the king salmon in 1980 range from .50 - .83 of the present fishery. The lowest detriment would accrue applying all reductions to the commercial fishery and the least fishery population reduction (.83).

The reduced harvestable salmon in 1980 would be 570,000 (.83) or 475,000 fish. Subtracting the sport catch of 138,000 this leaves 336,000 for commercial harvest or 95,000 less fish than the 432,000 fish that would have been harvested had the 0.83 reduction not occurred. At an average commercial value of $3.50 this represents a minimum detriment of $332,000 in 1980.

Following similar procedures, but recognizing that sport fishing catches may be severely reduced and commercial harvesting will continue to compete for the dwindling salmon supply. A maximum loss in sport catch in 1980 of 95,000 fish could occur along with no loss in commercial catch except the 5% reduction in harvest due to water development and urban growth.

Using the higher reduction in fishery population for 1980 of 0.50 (a reduction of 285,000 fish) the entire sport fishery (138,000 fish) could be lost along with 147,000 commerically harvestable salmon. This assumed loss corresponds with a loss of $1.38 million in recreationally harvested salmon (@ $10 per fish) and $246,000 in recreation days (@ $1 each) and $515,000 in commercial salmon harvest (@ $3.50 per fish) or a total maximum detriment of $2,141,000 in 1980.

The projected maximum and minimum detriments to the king salmon fishery for the years 1970-2020 are shown on Tables 12 and 13 .

AMERICAN SHAD

The American Shad fishery is not presently over-harvested and demand is not expected to exceed the annual harvestable supply of an estimated one million shad by 2020. Shad harvest in 2020 as projected by Skinner is 750,000 fish at a constant success ratio of 1.5. Reductions in the harvestable population

TABLE 12

KING SALMON FISHERY DETRIMENTS*
(Sport and Commercial Losses)

Year	Unimpaired Sport Fishery @		Maximum Harvest	Sport and Commercial Annual Detriments					
				Low Loss			High Loss		
	Use	Harvest		Sport	Commercial	Total	Sport	Commercial	Total
1970	216	127	600	--	--	--	--	--	--
1980	246	138	570	1119	--	1119	1626	515	2140
1990	317	168	540	1880	--	1880	1947	357	2354
2000	372	186	510	1956	--	1956	2232	242	2474
2010	422	198	480	2098	--	2098	2402	147	2549
2020	437	193	450	2208	--	2208	2367	112	2479

*Use in thousands of angler days
Harvest in thousands of fish
Detriment in thousands of dollars

@Projected by Skinner (149)

TABLE 13

KING SALMON FISHERY DETRIMENTS*
(Commercial Losses Only)

Year	Maximum Harvest	Pollution Impaired Harvest		Unimpaired Sport Harvest @	Commercial Harvest Loss		Annual Detriment	
		Low Loss	High Loss		Low Loss	High Loss	Low Loss	High Loss
1970	600	--	--	127	--	--	--	--
1980	570	475	285	138	95	285	332	997
1990	540	381	270	168	159	270	556	945
2000	510	347	255	186	163	255	570	884
2010	480	307	240	198	173	240	605	840
2020	450	270	225	193	180	225	630	786

*Harvest in thousands of fish
Detriments in thousands of dollars

@Projected by Skinner (149)

due to eutrophication coupled with increased demand have been assumed to decrease the success ratio in direct proportion to the total shad fishery population. The value of an American shad caught in a recreational experience is assumed to be $1/fish (average size 2 pounds).

Based on the above and using 1980 estimates of relative fish populations, the American shad detriments are computed as follows:

Using the relative fish population in 1980 as per previous example 0.68 (relative survival calculation), the reivsed success ratio is 0.68(1.5) = 1.02 fish/angler day. The 1980 demand as estimated by Skinner of 200,000 angler days would produce a harvest of 204,000 fish under the reduced fishery as opposed to 300,000 fish in the unimpaired situation. This loss of 96,000 harvested fish represents an annual detriment of $96,000 in 1980 for the 100 µg/l chlorophyll case example. The higher chlorophyll range (1980 of 200 µg/l corresponds to an annual loss of $225,000. The projected detriments to the American Shad fishery are given in Table 14.

TABLE 14

AMERICAN SHAD FISHERY DETRIMENTS*

Year	Unimpaired Sport Fishery @		Pollution Impaired Harvest		Sport Harvest Lost		Annual Detriment	
	Use	Harvest	Low Loss	High Loss	Low Loss	High Loss	Low Loss	High Loss
1970	125	187	--	--	--	--	--	--
1980	200	300	204	75	96	225	96	225
1990	200	413	206	106	207	307	207	307
2000	350	525	242	131	283	394	283	394
2010	425	638	261	159	377	479	377	479
2020	500	750	278	138	472	563	472	563

*Use in thousands of angler days

Harvest in thousands of fish

Detriment in thousands of dollars

@Projected by Skinner (149)

X. EFFECTS ON OTHER USES

Beneficial water-related activities other than fishing will be affected by projected nutrient enrichment of the Bay-Delta system. These activities are:

1. Shoreline Residential Developments
2. Boating and Navigation
3. Recreation and Aesthetics
4. Wildlife Propagation and Sustenance

Some of the effects of nutrient enrichment and salinity can be described and quantitative appraisals of the economic effects can be estimated.

SHORELINE RESIDENTIAL DEVELOPMENTS

An important trend in the present real estate market is the large scale development of shoreline areas for housing in the San Francisco Bay area. These developments include apartments, townhouses and single family residences. Typically, the improvements on these properties are designed to capture some of the amenities associated with the building site--a view of the Bay, proximity to water allowing boat docks in the "back yard," swimming and water skiing.

The market value of these recent developments (land and improvements) certainly is in the hundreds of million dollar category. No exact figure is offered because the rapidity of development means any estimate can be 50% in error in several years or less, due to rapid increases in the quantity of improved properties and substantial appreciation in the market values of all properties.

In the near future it can be expected that these shoreline residential developments will increase in quantity, unless the amenities associated with the shoreline are diminished or eliminated by environmental changes due to factors such as water pollution. If there is a decrease in amenities there will be a real loss to the Bay area, a loss that will result in some increase in "out of pocket" costs mitigating the effects of pollution and a much larger, but less measurable loss of amenities associated with the uses of San Francisco Bay.

The "out of pocket" costs for nuisance abatement can be estimated at millions of dollars per year for the future water quality problems in San Francisco Bay. The loss in amenities may be measured in billions of dollars. The exact magnitude of this loss to people residing along the shoreline will never be a scientific calculation. The magnitude of "out of pocket" costs can be predicted on the basis of present information and some reasonable assumptions about future conditions.

The magnitude of the perceived loss in amenities can only be related to a personal scale, with very little correspondence to a monetary scale--i.e., we can suggest alternative experiences to living near the shoreline, with a corresponding estimate of the cost of this alternative, but there is no scientific basis for assuming that this alternative cost can provide the same character and quantity of amenities that the original provides. It can be suggested what factors enter into a comparison of alternative sources of amenities, but the actual comparison is performed by an individual, and not usually on a scientific (hence replicable) basis.

A brief description of some of the recent shoreline developments is presented in Table 15. It should be noticed that the values of both the building sites and the improvements are greater than the usual housing developments in this area. The inference here is that these properties are made more valuable because of the shoreside amenities. If the amenities decreased it would be reasonable to expect some decrease in the values of these properties. At a minimum this decrease in value would equal the capitalized cost of the nuisance abatement costs. If the abatement techniques are not entirely successful, an additional decrease would adjust the value for the lower levels of the amenities.

Shoreline areas developed for residential use include eight developments in Marin County, four in Alameda County, three in San Mateo County and others in Sonoma County and Contra Costa County. Lot prices generally exceed $15,000 per lot, and homes are $30,000 - $75,000. Some areas were developed as either high rental ($235 - $475 per month) or condominium ($40,000 per unit) apartments or townhouses. The size of existing developments vary from less than 100 to over 1000 home sites. The potential for shoreline developments is large, and what will develop depends upon water quality, as well as many other factors.

Predicated on present nuisance abatement technology costs and the substantial development expected out of pocket costs were estimated for future nuisance control and maintenance costs attributable to water pollution.

Starting with the present minimum premium of about $10,000 per lot for shoreline versus typical subdivision lot prices and suggesting that possible future changes in shoreline amenities may cause an average reduction of $5,000 value per lot in the future, a change of $250,000,000 or so for shoreline residential property values can be calculated, (based on 50 square miles of developed Bay shoreline). Only a portion of this predicted change is considered related to Drain enrichment; since the major areas of intensive shoreline residential development are reasonably far from the discharge points proposed, 25% of the above change is assigned to the Drain effect on the general enrichment of the Bay area waters.

BOATING AND NAVIGATION

Water quality affects boating and navigational uses principally in the marine regions of the Bay where various fouling organisms and marine borers

TABLE 15

SHORESIDE RESIDENTIAL DEVELOPMENTS
(Incomplete Listing)

Development	Description	Cost*
Marin County		
Harbor Point	Homesites, some on water	$28,000-$50,000/lot
Corta Madera Canal	Homesites, all with water frontage	$14,750-$19,000/lot
Bel Marin Keys	Large water oriented development	$30,000-$49,000/house
Shelter Bay	1-4 Bedroom Units, Units on Water	$235-$475/mo. rent
Alameda County		
Bayview Estates	Waterport Homes	$31,950-$36,500/house
Bayview West	Condominium	Avg. $30,000/house
Lagoon Homes	Homes	$47,750/house
San Mateo County		
Foster City	Lagoon and Bay access, homesites, apartments	$28,000-$75,000/house $15,000-$25,000/lot
Mariners Island	Lagoon Townhouses	From $33,500/home

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*All cost figures are approximate and not necessarily comparable with each other due to differences in home size, lot size, water access and other features. All costs are as received during 1966 from real-estate brokers by personal contact or from advertisements and other published sources. The tabulated developments represent only a sampling of those known to exist, and those mentioned above are selected only on the basis of information at hand. Inclusion or exclusion of any water-oriented development (large or small) in no way constitutes any qualitative judgment of the real-estate.

thrive. Fouling organisms such as algal scums, barnacles, tunicates, and mussels attach themselves to boat hulls, wharves, and channel buoys. Fouling organisms must be removed from boat hulls and marker buoys before protective paints are broken down or damages will result (i.e. corrosion, marine borers). Pleasure boats which are kept in Bay marinas generally undergo hull maintenance every 9-12 months. Boats in some enriched areas require more frequent hull maintenance (6-8 months). Fouling organisms may respond to nutrient enrichment directly (algal scums) or indirectly (barnacles). Barnacles and other fouling animals consume diatoms and other microscopic life in surrounding waters.

A survey of twelve boat maintenance yards was carried out to assess the magnitude and nature of boring and fouling problems in the Bay waters. A questionnaire was prepared, which included the following questions:

1. What organisms are most frequently encountered on boat hulls and water front structures in your area, and which are the greatest nuisance?

2. How often does a boat owner in your area have to clean his hull of fouling organisms or repair damages by borers?

3. What are your charges for hull maintenance? (Separate hull cleaning and repair from painting costs).

4. In your opinion, are boring and fouling problems on the increase?

5. Have you needed to repair wharf structures damaged by boring or fouling organisms?

The following is a summary of the information received:

1. The most frequently encountered nuisance organisms are barnacles, slimes, grasses and mussels (fouling organisms) and teredo and Limnoria (boring organisms). The sequence of appearance on boat hulls is generally slimes (periphyton), macroalgae (Ulva, etc.) and barnacles, mussels, and borers. The borers appear after the hull paint has broken down or chipped.

2. The average haulout frequency is nine months to one year. When racing boats are involved, more frequent cleanings are given. In an enriched area between Alameda Island and the Oakland shore haulout frequencies were from six to eight months from the three yards surveyed in this area.

3. Charges for hull maintenance ran from about $2.50 - $3.50 per foot of hull. In some yards haulout, hull cleaning and painting were charged separately based on labor and material charges.

4. All yards (except one where pollution in the marina was gross) stated that either boring or fouling or both were on the increase. Most believed that fouling problems were increasing.

5. A few yards had lost piling, but generally the wooden wharf structures last 25 years or more if creosote treated.

Contacts were made with the U. S. Navy and the U. S. Coast Guard to gain knowledge of their experience with fouling problems on operating ships, those in the mothball fleet as well as maintenance problems associated with navigational structures (buoys, etc.).

The Navy maintains their line vessels at established intervals depending on the class of vessel and does not keep a record of costs associated particularly with marine fouling organisms. Of the vessels which remain in the Bay, such as the "moth ball" fleets at Mare Island and Suisun Bay, the hull maintenance is about once every five years. Marine growths are more prolific on the Mare Island fleet where salinity levels are typically higher. The Navy does considerable testing and development of anti-fouling paints here.

Operators of the two Coast Guard tenders, which operate principally in the Bay, identified areas where growths appeared to be heaviest. These were at the Oakland end of the Bay bridge, near Richmond and in South Bay. Growths were low in Suisun Bay where waters are fresher and in San Pablo Bay where mud but little growth deposited on the structures.

Hull maintenance frequencies may increase to two haul outs per year for boats berthed in enriched saline areas, particularly where friction losses are important such as in sailboat racing. Improved anti-fouling paints, chemical controls of growths, and resistant hull materials will probably offset some of the expected increases in pleasure boat hull maintenance costs.

Projected marina berths and hull maintenance costs for pleasure boats are presented in Table 16 . Hull maintenance projections are based on 100% berth occupancy, 20 foot average craft length, $3.00 per lineal foot hull maintenance charges and one maintenance haul out per year.

TABLE 16

PROJECTED BOAT HULL MAINTENANCE COSTS

	1965	1990	2020
Marina Berths	6,500	15,000	30,000
Hull Maintenance $1000 per year	392	900	1,800

The above projected hull maintenance costs would necessarily double if enrichment lead to two haulouts per year.

One-half of the projected increase in hull maintenance is estimated to be a result of the Master Drain enrichment of the Bay.

RECREATION AND AESTHETICS

Recreational uses of the Bay-Delta system include water related activities such as swimming, water skiing, skindiving, pleasure boating and fishing and peripheral activities including sunbathing, hiking, hunting, and bird-watching. Residential and commercial areas also derive value from their proximity to or view of the water, utilizing the shore areas as a recreational site or for aesthetic appeal. The effect of possible future water quality changes on fishing, shoreline residential developments and boating have been discussed in previous sections. The remaining categories of recreation and aesthetic benefits that are derived from the Bay-Delta system are a substantial source of benefits to residents and visitors to the Bay-Delta area.

The Stanford Research Institute (SRI) report "Recreation and Fishery Values in the San Francisco Bay and Delta" prepared for the FWPCA, contains projected recreational values for the Bay-Delta system (151). These projections for all recreation categories except fishing for 1990 and 2020 are reproduced below.

TABLE 17

ECONOMIC BENEFITS OF RECREATIONAL ACTIVITIES

(Median Values)

	Benefits in Millions of Dollars	
	1990	2020
Central Bay	$ 7.51	$17.58
San Pablo Bay	3.71	6.55
Suisun Bay	3.21	5.67
Delta	10.35	18.82
Total	$24.78	$48.62

The recreational categories included in the above are 1) sun bathing and swimming, 2) sightseeing, 3) boating, 4) water skiing, 5) picnicking, 6) nature walking, 7) hunting, 8) camping, 9) hiking. The total projected recreational values have been placed at $20 M in 1990 and $40 M in 2020. This reduction of the SRI projections reflect the fact that a portion of the boating and hunting benefits are considered separately in this report.

An example of the effects of nitrogen enrichment can be the problem of blue-green algae. In recent years, bluegreen algal populations have surpassed nuisance levels in some enriched dead-end sloughs of the Delta during the summer recreational season. In the future fresh water channels of the Delta may become noticeably discolored or support floating scums of blue-green algae at nitrogen concentrations above 1.5 mg/l.

Nuisance blue-green algal populations occur in the fresh water reaches of the Potomac River estuary. The blue-green algal genera which commonly occur in the Potomac estuary include *Microcystis*, the genus which has been dominant in enriched, dead-end sloughs in the Sacramento - San Joaquin River Delta, (152). Nuisance conditions, including offensive scums, discoloration, and odors, occur in the area of Mount Vernon and upstream during the summer. Blue-green algae are not found in abundance in saline waters and the nuisance-causing genera are normally confined to fresh water including fresh water portions of estuaries (less than 1000 mg/l TDS) (153). Nitrogen levels (organic) corresponding with noticeable discoloration (50 µg/l chlorophyll) caused by blue-green algae are found in the enriched tidal Potomac, near Washington, D.C. (154). More extreme discoloration, as a result of higher chlorophyll levels (100 µg/l) corresponding to higher organic nitrogen levels (1.5 - 2.0 mg/l), has been reported in the Potomac.

Lackey (1966) expects blue-green algae to increase in numbers in the fresh water portions of the estuary (11). He cites *Microcystis*, *Anabaena*, *Gleoscopos*, *Merismopedia*, *Oscillatoria* and *Gleocystis* as species which will thrive in enriched freshwater. He also expects more green algae, such as *Chlorella* and *Nannochloris* as well as *Scenedesmus* and *Kircheriella*. The diatom *Cyclotella* is expected to continue to be a major plankton component. The consequence of these algal growths may be that the recreationist experiences less enjoyment of swimming and water skiing in the Delta area, or he transfers his recreational demand toward another area, perhaps a place further away. In the first case, the value of his recreational experience is decreased, while for the second case, the recreating may provide the same type of benefit, but the consumer has incurred higher costs to realize the recreational experience. Either case represents a loss in value, perhaps only 10%, but possibly as high as 50% if travel to another site is involved.

Based on this possible 10-50% decrease in value and the estimated values of $20 million and $40 million for these "other" recreation and aesthetic experiences, the possible economic magnitudes of the changes in water quality are $2-10 million and $4-20 million in 2020. Fifty percent of these estimated detriments are assigned to the Master Drain, although a higher proportion may be warranted, due to the projected effects of the Drain on the Delta area.

WILDLIFE PROPAGATION AND SUSTENANCE

There are over 100 species of birds associated primarily with the aquatic habitat (i.e. ducks, geese, swans, shorebirds, gulls, etc.) of the San Francisco Bay-Delta system. Predominant among these are the waterfowl which are a heavily exploited wildlife resource. The Bay area consistently produces about 25 percent of the statewide duck kill, and hunter success is usually above the statewide average. An examination of various figures on abundance shows no clear cut trends in population, although there are frequent large-scale fluctuations which are believed due to natural environmental factors such as weather. The Bay and Delta area is of great value to waterfowl because it affords them a feeding ground as well as a sheltered resting place. Limited nesting also takes place. In addition, there are five refuges or waterfowl management areas in the Bay-Delta area. Also of considerable value are the relatively large expanses of tide flats, which at low tide serve as a major feeding ground for a tremendous number and variety of shore birds. The overall abundance of shorebirds appears to be less than the waterfowl, but the birds are more widely distributed. There is some indication that the abundance of certain species of shorebirds has decreased considerably in the last two or three decades, although the cause is unknown.

Waterfowl hunting has been valued at over $500,000 per year. Hunting pressures are expected to increase, although hunter success is expected to decline from a present bag of two birds per hunter day to one bird per hunter day by 2020 (149). Hunting pressures, water quality degradations and marshland reclamation will reduce waterfowl populations in the Bay area and effectively reduce migratory bird populations of the Pacific Flyway which depend upon the Bay and Delta marshlands for wintering grounds.

Some of these changes in wildlife can be relating to a monetary measure, such as a possible decrease in the hunting success caused by a reduction in waterfowl populations using the Bay-Delta area. Nature hikers also are affected, but the greatest impact may be felt by the protected forms of wildlife, and they do not have a monetary equivalent. Fifty percent of the projected loss to wildlife is assigned to the Drain, although a higher proportion may be justified on the basis of the proximity of major waterfowl areas to the Master Drain discharge points.

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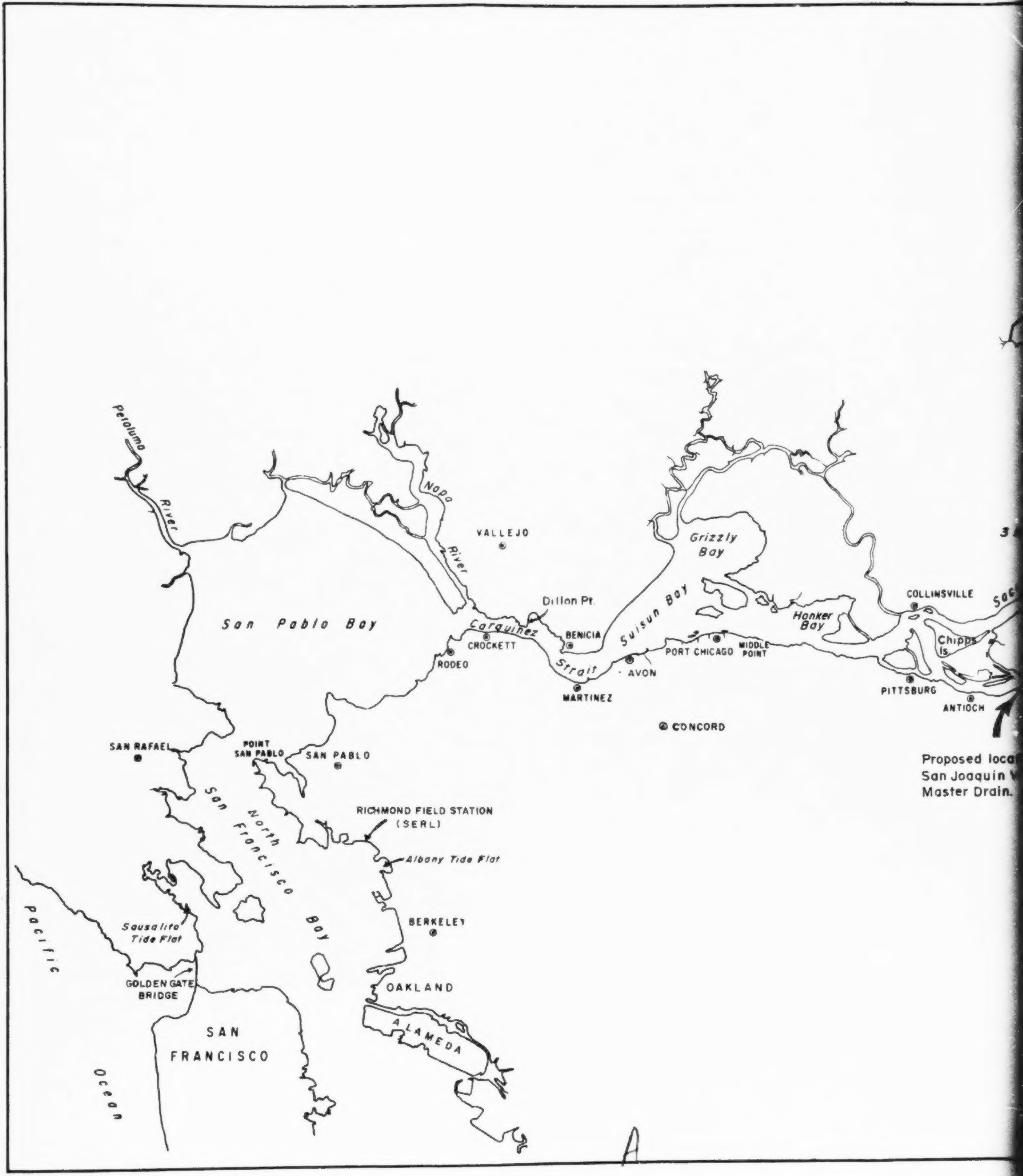
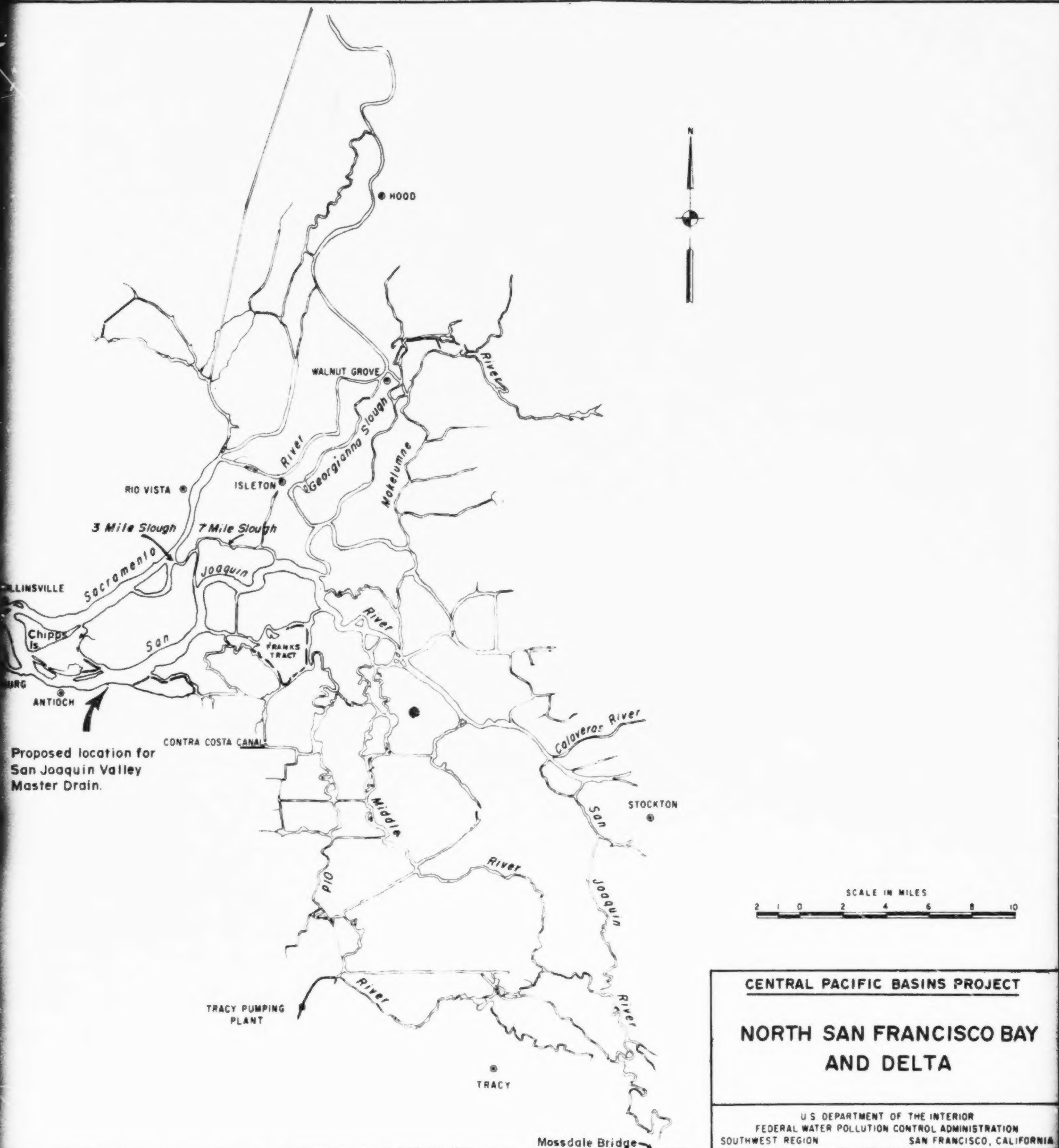

Petaluma River
Napa River
VALLEJO
Grizzly Bay
3
Dillon Pt.
San Pablo Bay
Carquinez Strait
CROCKETT
BENICIA
Suisun Bay
COLLINSVILLE
Sac
Honker Bay
Chipps Is
RODEO
PORT CHICAGO
MIDDLE POINT
AVON
MARTINEZ
PITTSBURG
ANTIOCH
CONCORD
Proposed loca
San Joaquin V
Master Drain.
SAN RAFAEL
POINT SAN PABLO
SAN PABLO
North San Francisco Bay
RICHMOND FIELD STATION (SERL)
Albany Tide Flat
Pacific Ocean
Sausalito Tide Flat
BERKELEY
GOLDEN GATE BRIDGE
OAKLAND
SAN FRANCISCO
ALAMEDA
A


N
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River
Mokelumne
RIO VISTA
ISLETON
3 Mile Slough
7 Mile Slough
Sacramento
Joaquin
LLINSVILLE
Chipps Is.
San
FRANKS TRACT
River
URG
ANTIOCH
CONTRA COSTA CANAL
Calaveras River
STOCKTON
San
Middle
Old
River
Joaquin
River
TRACY PUMPING PLANT
River
TRACY
Mossdale Bridge
SCALE IN MILES
2 1 0 2 4 6 8 10

Proposed location for San Joaquin Valley Master Drain.

CENTRAL PACIFIC BASINS PROJECT

NORTH SAN FRANCISCO BAY AND DELTA

U S DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMINISTRATION
SOUTHWEST REGION SAN FRANCISCO, CALIFORNIA

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FOLDOUT MAP